The Influence of Progressive Static Load on the Ability of Dental Implants to Withstand Overloading Forces: An Experimental Study in Dogs

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Purpose: To examine the effect of controlled progressive orthodontic loading on bone around implants subjected to overloading forces. Materials and Methods: Bilateral edentulous alveolar ridges were created in the posterior maxilla of five beagle dogs and left to heal for an 8-week period, after which 40 implants were placed. In the overloading group (OL), 16 implants were inserted and left to osseointegrate for 16 weeks; impressions were made, and metal crowns were mounted on with supraocclusal contacts with the antagonist teeth. Implants were exposed to dynamic overloading for 16 weeks. In the progressive loading + overloading group (PL+OL), 16 implants were left to osseointegrate for 8 weeks, and custom abutment cores were fabricated and coupled by pairs with Ni-Ti orthodontic springs. Ascending static forces of 100g, 200g, and 300g were each applied for a 3-week period, for a total 9-week progressive loading period. Thereafter, metal crowns with supraocclusal contacts were adapted, and a 16-week overloading protocol for implants was followed as for the overloading group. In the unloaded control group (UL), eight implants were inserted and left uncovered and unloaded for 32 weeks, that is, until the end of the experimental period, at which point all 40 implants were removed with the surrounding bone. Histologic, histomorphometric, and statistical analysis followed.

Results: Higher bone-to-implant contact percentage was reported for the OL group (P = .006) and PL+OL group (P < .001) compared with the UL group. Between the OL and PL+OL groups, the addition of progressive loading did not increase the bone-to-implant contact percentage (P = .225). Bone density 1 mm and 2 mm distant to the threads did not differ significantly between the three groups. Significantly lower crestal bone resorption was detected around OL group implants (P = .006) and PL+OL group implants (P = .004) compared with the UL group implants. The implant success rate was 87.5% for the UL group, 67.5% for the OL group, and 87.5% for the PL+OL group. Conclusion: The application of controlled progressive orthodontic loading on osseointegrated implants preceding overloading forces did not increase bone-to-implant contact. When applied, overloading significantly increased bone-to-implant contact compared with the unloaded implants. A significantly higher implant success rate was reported in the PL+OL group compared with the OL group.

Keywords: bone remodeling, crestal bone resorption, occlusal load, overload, progressive load, static load

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incriminated.2,6–8 These two factors may overlap and interact in a vicious circle; however, in a healthy peri-implant environment, it is still a matter of controversy whether occlusal overloading may lead to or contribute to late implant failures. Overload is defined as the load that "exceeds the mechanical or biologic load-bearing capacity of the osseointegrated oral implants or the prosthesis, causing either a mechanical failure or failure in the osseointegration."9

Frost presumes that bone has a control system, referred to as a "mechanostat," that acts via modeling and remodeling to maintain constancy of the mechanical environment of cells when external loading conditions change.10 Frost also stated that mechanical forces may have either a positive or negative effect on bone tissue11 and, therefore, on the bone surrounding a loaded implant. Most of the studies failed to correlate either static or dynamic forces with the induction of peri-implant bone loss in the absence of soft tissue infection.12–23 On the contrary, in most of these studies, bone density around implants was increased at the end of the experimental loading period. There are, however, studies providing data that implicate load as a causative factor for the loss of osseointegration.24–26

Bone density is related to the strength and elastic modulus of bone.27 By extension, long-term implant success is dependent on the percentage of bone-to-implant contact (BIC) at the interface level. Studies have indicated that BIC depends on the pristine local site bone density28 and have reported reduced success rates when implants are placed in poor-quality bone.29,30 This means that the higher existing bone is in contact with the implant surface at the time of implant placement, the higher the BIC will be when the implant is osseointegrated.

In cases of poor-quality bone sites, an increase of the bone density around an implant during the healing period would improve the BIC and, hence, the clinical outcome. It has been suggested that applying forces on an implant in a progressive pattern will give time for peri-implant bone to grow denser and more efficiently tolerate the forthcoming mastication forces.22,31–34 The method is applied by controlling the surface of the occlusal table, the amount and direction of the occlusal contacts, and the presence of cantilevers, and by following special dietary instructions.35 The efficacy of this procedure was based on empirical clinical observations; however, recently, histologic evidence of the effectiveness of progressive loading as a method to significantly enhance bone-to-implant contact during the osseointegration period was provided.36 Nevertheless, it is still uncertain if progressive loading on osseointegrated implants may also assist bone in tolerating any excessive occlusal loading. The reason, if any, for the loss of osseointegration of already-integrated implants due to overloading forces is not yet clearly evident.37,38

The purpose of the present study was to provide histologic and histomorphometric data of the behavior of bone tissue around implants under occlusal overload and progressive load followed by occlusal overload.

**MATERIALS AND METHODS**

The protocol of the study was approved by the standing committee on animal research at the Veterinary Headquarters of Karditsa Prefecture, Thessalia, Greece (approval number 2539/2003).

**Clinical Procedures**

Five adult beagle dogs were used (weighing approximately 13.5 to 17.5 kg each, mean age of approximately 2.5 years).

During all surgical procedures, the animals were pre-anesthetized with xylazine 0.7 mg/kg (Rompun, Bayer) intramuscularly. Anesthesia was induced with intravenous administration of sodium thiopentone (Pentothal, Abbott Laboratories) and maintained with a mixture of isoflurane (Forenium, Abbott Laboratories) and oxygen in a semi-closed breathing circuit. Additionally, local infiltration of articaine with norepinephrine (1:100,000) (Ubiestein Forte, 3M ESPE) was administered for reduction of hemorrhage and post-operative pain.

In all dogs, the premolars as well as the first molar of the maxilla were gently extracted bilaterally. Thin elevators were used to remove any separated root remnants. All wounds were closed with the aid of resorbable vicryl 4/0 sutures (Monocryl, Ethicon). Eight weeks were allowed to achieve healing of the extraction sockets.

**Phase I: Implant Placement**

All five dogs received eight implants each, four in the left side and four in the right side of the maxilla. A total of 40 implants of 4 mm diameter and 8.5 mm length with Osseotite surface and machined neck were inserted (Biomet 3i). Sixteen implants represented the overloading group (OL), 16 implants comprised the progressive loading followed by overloading group (PL+OL), and eight implants constituted the unloaded control group (UL).

Implant surgery was performed by a midcrestal incision on the healed edentulous alveolar ridge, and a full-thickness mucoperiosteal flap was elevated. The alveolar crest was flattened in order to reach adequate ridge width by the use of rotary instruments. Implants were placed according to the manufacturer's guidelines. Copious irrigation with sterile saline...
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accompanied bone drilling. Implants were inserted in a crestal apico-coronal position and parallel to each other. Overloading and progressive plus overloading group implants were divided by pairs. The centers of the implants of each pair were planned to be approximately 15 mm apart. The pairs of the right sides of dogs No. 1, 2, 3, and 4 were registered as implants of the overloading group, while the pairs of implants inserted in the left sides of dogs No. 1, 2, 3, and 4 were registered as implants of the progressive loading plus overloading group. Implants registered in the unloaded control group were inserted at random positions, four at each side of the maxilla of dog No. 5.

Flaps were repositioned in place using resorbable 4/0 vicryl sutures (Monocryl, Ethicon), and antibiotics were administered intramuscularly for 5 days (Synulox, Pfizer). Implants were left to osseointegrate in all animals for 8 weeks.

Phase II: Abutment Connection and Progressive Loading (PL+OL Group)

At the end of the 8-week osseointegration period, all 16 implants of the progressive loading plus overloading group were exposed and clinically inspected. A single custom transmucosal metal abutment was attached to each implant and secured with a screw (Titanium Hexed Screw, Biomet 3i). Abutments were cast in the laboratory with a hexed platform with the aid of a plastic UCLA component (Biomet 3i). Implants were left to osseointegrate in all animals for 8 weeks.

Fig 1  Implants were connected by pairs, through holes made on the abutments, by closed-type Ni-Ti orthodontic spring.

According to the literature, the force that was delivered by Ni-Ti springs remained constant for the experimental period of the present study. Nevertheless, to avoid a strength decrease, the condition of the springs was checked every week. Abutments were brushed three times per week using a 0.2% chlorhexidine digluconate solution (Chlorhexil, Intermed Pharmaceutical Laboratories) to avoid peri-implant inflammation. At the beginning and at the end of the progressive loading period, the distance between the abutments of all implant pairs was checked with the aid of a digital micrometer (Insize), and values were recorded. During this progressive loading period, implants of the overloaded and unloaded groups remained uncovered.

Phase III: Implant Overloading (OL and PL+OL Groups)

At the end of the 9-week progressive loading period, abutments and springs were removed from the progressive loading plus overloading group implants. Implants of the overloading group were uncovered as well. On all the implants of the overloading and progressive loading plus overloading groups, impression copings were adapted (Biomet 3i), impressions were taken, and the casts were mounted in semi-adjustable articulators. Separate metal crowns were fabricated for each implant, and a premature supraocclusal contact with the antagonist teeth was created with an inclined occlusal plane, so not only axial but lateral forces would be applied (Fig 2). This excessive height of the suprastructures resulted in an increased anterior vertical dimension of 3 to 4 mm. Crowns were placed on the implants and left to over-occlusal dynamic loading for a period of 16 weeks. Crowns were brushed three times per week using a 0.2% chlorhexidine digluconate solution (Chlorhexil, Intermed Pharmaceutical Laboratories), and implants were clinically inspected for signs of mobility and inflammation. As for phase I, during this overloading period, the implants of the unloaded group remained uncovered.

Fig 2  Separate metal crowns placed on the implants.
Bone Specimen Harvesting
At the end of the overloading period, all implants were checked for any sign of mobility. After mucoperiosteal flap elevation, the maxillae were dissected in all five dogs. Bone blocks containing the implants were removed without the need to sacrifice the animals (Ethical Committee acceptance protocol number 2539/2003, Veterinary Headquarters of Karditsa Prefecture) as described elsewhere. Flaps were sutured together with the nasal mucosa using resorbable 4/0 vicryl sutures (Monocryl, Ethicon). Dogs were followed for a period of 2 weeks and sent for adoption. Blocks were cut to smaller parts containing one implant each, fixed in a 10% neutral buffered formalin solution, and sent for histologic processing.

Histologic Preparation and Histomorphometry
The specimens were dehydrated in increasing grades of ethanol, ending in absolute 100% alcohol, infiltrated in resin (Remacyl, Istituto di Microscopia Elettronica, Clinica Sant’Ossola Hospital), and polymerized for 12 hours under blue light.

Sections were prepared using the cutting/grinding method with the aid of a Micromet high-speed rotating blade microtome (Remet) at 200- to 250-μm thickness and ground down to approximately 40 to 50 μm with a grinding machine (LS2, Remet). The histologic slides were stained with toluidine blue and basic fuchsin solutions.

The histomorphometric analysis was performed by digitalizing the images from the microscope (Zeiss) via a JVC TK-C1380 Color Video Camera (JVC Victor Company) and a frame grabber. Digital image analysis software (IAS 2000, Delta Sistemi) was used for the measurements. The BIC was presented as the percentage of the linear measurement of mineralized bone in direct contact with the implant surface, over the total length measurement, that is, the most coronal BIC until the apex of the implant, on each side. Bone density percentage (BD%) was measured at two different regions extended 1 mm (BD-1) and 2 mm (BD-2) horizontally from the tips of the implant threads and was expressed as the percentage of bone area out of the total measurement area. Finally, crestal bone resorption was measured linearly from the implant platform to the first BIC and expressed in millimeters.

Statistical Analysis
Data are summarized, by group and overall, using their median and interquartile range (IQR) and presented graphically using box plots. Differences between groups were assessed through quantile (median) regression models. The actual BIC, BD-1, BD-2, and crestal bone resorption measurements were treated as the dependent variables, and the group protocol was entered as a categorical explanatory variable in the respective models. The fact that repeated measurements, using different protocols, were taken on each dog was taken into account by allowing for intracluster correlation between measurements taken on the same dog.

For the analysis of differences in bone density (%) measurements between different locations of measurement relative to the threads (1 mm vs 2 mm), similar median regression models were used with the measurements entered as the dependent variable and the location as a binary explanatory variable. Since in this case there were repeated measurements taken on each implant (and each dog), the combinations of implants and dogs were considered as the clustering unit. All reported $P$ values are based on the results of the aforementioned models. The level of significance was set at $P \leq .05$.

RESULTS
Clinical Outcomes
In the unloaded control group, one implant was found to be mobile at the time of bone specimen harvesting (success rate: 87.5%). In the progressive loading plus overloading group, 2 out of the 16 implants were found to be not stable at the end of the experimental period (success rate: 87.5%). All implants of this group at the end of the progressive loading period healed uneventfully and were found to be clinically stable, while the distances between the implants remained unchanged. In the overloading group, 5 out of the 16 implants were found to be mobile at different time points from the beginning of the overloading period (success rate: 68.75%). The two lost implants of the progressive loading plus overloading group as well as the three out of five lost implants from the overloading group belonged to the same animal. This animal, which had a constant aggressive behavior, biting the cage and the feeding vessels, exhibited a low implant success rate (37.5%—3 out of 8 implants).

Histologic Results
The unloaded control group bone showed a cancellous low-density structure with composite morphology. New and old lamellar bone, woven bone, and osteoid were all found in the specimens. Moreover, a lot of cement lines were observed as well as sites of bone remodeling. Peri-implant bone in this group showed a low degree of remodeling with a not-well-organized functional pattern of the bony trabeculae (Fig 3a).

In the overloading group, bone was denser and more mature even at the coronal implant regions (Fig 4a). A lot of cement lines were observed separating the different stages of bone formation as well as sites of osteoid deposition, bone formation, and resorption (Fig 3b). Some
specimens exhibited bone hypertrophy, fully remodeled bone with primary and secondary osteons around implant threads, very small marrow spaces, and corticalization of the peri-implant bone (Fig 4b). Generally, in this group, all bone ages may be observed: woven bone, new remodeled bone, and old lamellar bone.

The crestal bone in the progressive loading plus overloading group was much better preserved at all specimens (Fig 5a). In most implants of this group, no crestal bone resorption areas were detected. However, layers of woven bone were often observed, mainly coronally (Fig 5b). At all other
sites, along the implant body surface, there is fully dense bone.

Certain implants of the overloading and progressive loading plus overloading groups exhibited regionally different degrees of bone resorption and loss of BIC. In an implant of the overloading group, dense bone was observed only at the half apical portion of the implant body (Fig 6a), while at the coronal half there was a peri-implant pocket (Fig 6b). An implant of the progressive loading plus overloading group was osseointegrated, but the quantity of bone around the implant was low. At all sites, bone was dense; however, it was under the process of resorption due to overloading. Nevertheless, no inflammatory cells were detected (Figs 7a and 7b).

The implants that exhibited a different degree of mobility histologically showed loss of osseointegration by means of fibrous integration (Fig 7c) or complete absence of bone in contact with the implant surface (Fig 6c).

**Histomorphometric Measurements**
The overloading group (median: 59.74) as well as the progressive loading plus overloading group (median: 68.35) exhibited higher BIC% than the unloaded group (median: 34.18). Loading significantly increased BIC%
around implants of the overloading group \((P = .006)\) and progressive loading plus overloading group \((P < .001)\) when each group was compared with the unloaded group. Between the overloading and progressive loading plus overloading groups, the addition of progressive loading increased the BIC\% with a difference that was not statistically significant \((P = .225)\) (Table 1).

The median BD-1\% measured 60.80 for the unloaded group, 66.88 for the overloading group, and 62.62 for the progressive loading plus overloading group. The differences in BD-1\% were not statistically significant between the overloading and unloaded groups \((P = .512)\), progressive loading plus overloading and unloaded groups \((P = .825)\), and between overloading and progressive loading plus overloading groups \((P = .666)\). The median values of BD-2 were 56.91\% for the unloaded group, 63.64\% for the overloading group, and 56.94\% for the progressive loading plus overloading group. There was not a significant difference in BD-2\% between the overloading and unloaded groups \((P = .554)\), progressive loading plus overloading and unloaded groups \((P = .732)\), as well as between overloading and progressive loading plus overloading groups \((P = .407)\). Similarly, in all groups, the difference between BD-1\% and BD-2\% was not significant (unloaded group: \(P = .446\), overloading group: \(P = .700\), and progressive loading plus overloading group: \(P = .064\)); however, in the PL+OL group, this difference was marginally not statistically significant (Table 1).

Median values of the crestal bone resorption were measured (in mm) to be 2.25 in the unloaded group, 1.63 in the OL group, and 1.92 in the progressive loading plus overloading group. Significantly lower crestal bone resorption was detected around overloading group implants \((P = .006)\) and progressive loading plus overloading group implants \((P = .004)\) when each group was compared with the control unloaded group implants. Between the overloading and progressive loading plus overloading groups, crestal bone resorption did not present a significant difference \((P = .281)\) (Table 1).

The distribution of measurements by group and the distribution of measurements of BD\% 1 and 2 mm distant to the implant threads are shown in the box plots of Figs 8 and 9, respectively.

**DISCUSSION**

The applied occlusal force on an implant is transferred as stress to the peri-implant bone, which results in bone deformation, which is reported as strain and is abbreviated with the Greek letter \(\varepsilon\). Various bone experimental studies revealed that bone deformation differs from site to site and between individuals, an observation that led to the formulation of Frost’s “mechanostat” theory.10,44 Based on this hypothesis, bone reaction to strain may be divided into five ranges without definite boundaries:44–46: (1) disuse range (below 1,000 \(\mu\varepsilon\)), (2) normal load (1,000 to 1,500 \(\mu\varepsilon\)), (3) mild overload (1,500 to 3,000 \(\mu\varepsilon\)), (4) pathologic overload (above 3,000 \(\mu\varepsilon\)), (5) acute fracture (around 25,000 \(\mu\varepsilon\)). At the disuse range, bone atrophy and resorption are observed, while at the range of normal load, there is homeostasis—the bone mass is in a steady state. Nevertheless, the threshold between mild overload range and pathologic overload range is of great importance in correctly interpreting

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**Table 1** Median Values for Each Parameter Measured for UL, OL, and PL+OL Groups with Interquartile Range

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<tr>
<th>Parameter</th>
<th>UL group</th>
<th>OL group</th>
<th>PL+OL group</th>
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<tbody>
<tr>
<td>BIC% (IQR)</td>
<td>34.18 (27.45, 48.03)</td>
<td>59.74 (45.67, 74.36)</td>
<td>68.35 (55.56, 74.44)</td>
</tr>
<tr>
<td>BD-1% (IQR)</td>
<td>60.80 (54.31, 62.76)</td>
<td>66.88 (52.31, 77.18)</td>
<td>62.62 (57.79, 70.85)</td>
</tr>
<tr>
<td>BD-2% (IQR)</td>
<td>56.91 (51.55, 61.69)</td>
<td>63.64 (45.82, 70.15)</td>
<td>56.94 (52.17, 65.79)</td>
</tr>
<tr>
<td>CBR (in mm)</td>
<td>2.25 (1.91, 2.30)</td>
<td>1.63 (1.31, 2.04)</td>
<td>1.92 (1.72, 2.04)</td>
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Total N (%)

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<th>7 (100.0)</th>
<th>11 (100.0)</th>
<th>14 (100.0)</th>
<th>Overall: 32 (100.0)</th>
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BIC = bone-to-implant contact; BD-1 = bone density 1 mm from the implant threads; BD-2 = bone density 2 mm from the implant threads; CBR = crestal bone resorption; UL = unloaded; OL = overloading; PL+OL = progressive loading plus overloading.
study results. Below this threshold, strains will cause bone mass to increase, while above it, fatigue phenomena or bone resorption will appear.

Whether peri-implant bone reaction to a load may remain within physiologic limits or enter the pathologic overload range is dependent upon many factors, among which are the percentage of bone-to-implant contact (BIC%), the histologic type of bone, and the magnitude, duration, and direction of the applied force.\textsuperscript{35,47} Thus, the effects of the load cannot be evaluated by measuring the amount of forces, but by measuring the amount of strain induced in the bone matrix by the load. However, this value is difficult to measure. In all animal studies, including the present study, excessive strain is induced by occlusal overload established by the premature supraocclusal contacts, as previously repeatedly described.\textsuperscript{14,20,23,24,48}

The threshold limits of bone adaptation to strain reported\textsuperscript{10,44} are general limits for bone tissue, and it remains obscure how they would apply to peri-implant bone.\textsuperscript{49} However, the peri-implant bone environment may exhibit great variety in density and histologic type. It is well reported that the mechanical properties of cortical bone differ widely from that of the trabecular bone.\textsuperscript{50,51} In the present study, implants were inserted in the porous trabecular and low-quality bone of the dog posterior maxillae, as this is the most vulnerable macroscopic type of bone-to-implant failure.\textsuperscript{29,30} In particular, for the trabecular bone, due to its porous characteristics, a very wide range of Young's modulus (from 6.9 to 199.5 MPa) is reported,\textsuperscript{52} a fact that, from one point of view, puts strain measurements under question and, from another point of view, lends peri-implant trabecular bone the ability to respond very differently to applied forces.

It was demonstrated that, during loading, the maximum force is concentrated in the contact area of cortical bone and the implant body and stress is distributed to the cortical bone itself, which means that the cortical bone supports most of the applied force, protecting, in a way, the more vulnerable trabeculae of the cancellous bone.\textsuperscript{53} However, in areas of the posterior region of the maxilla, as in the present study, cortical bone mass is largely lacking, and all stress is transmitted to the cancellous bone that supplies the implant, which has less load-bearing capacity. Due to the porous nature of cancellous bone, a much smaller area is in contact with the implant surface and greater stress is concentrated.\textsuperscript{54}
The design of the implant is considered to have a significant effect on local load concentration, crestal bone resorption, and bone healing around dental implants. It is reported that vertical force of 500 N is considered as overload and may cause damage to cortical bone in specific implant design, while occlusal forces beyond 1,000 N evoke peri-implant overloading characteristics that range considerably among different implant designs. Adult human occlusal force is measured well beyond those values and therefore, depending on implant design, may provoke peri-implant overloading detrimental effects.

Apart from the magnitude of force applied on an implant, other force parameters play an equally important role in peri-implant bone adaptation, such as the frequency and the duration of the loading cycles, as well as the periods of rest between load bouts. The hyper-aggressive behavior of one of the experimental animals and the effects that provoked on peri-implant bone gives indication toward the influence of these parameters.

In the present study, the dog animal model was selected, since comparability between magnitude of vertical occlusal force and bone quality in humans and dogs shows high similarity. The placement of the implants was performed in the low-density bone of the maxilla, as described in the first part of this study series, to better show a possible increase of bone density induced by the load. Nevertheless, as pointed out in many review articles, results from animal studies should not be extrapolated in clinical practice without skepticism, and therefore, results should be interpreted with caution.

Many studies are dealing with the influence of loading forces on peri-implant bone. However, the literature does not give satisfactory explanation of why some of the forces are beneficial while others are detrimental to the surrounding bone. This is mainly because experimental protocols follow different methodologies in relation to the species of laboratory animals involved; the biologic state and histologic type of bone examined; the implant surface and the nature, magnitude, and duration of the forces applied. Hence, it is difficult to safely compare results among experimental studies. A limited number of studies provide evidence that mechanical load affects interfacial bone modeling and remodeling; provokes bone resorption, or even causes loss of osseointegration. On the contrary, many other studies show that mechanical load increases the BIC and the bone volume of peri-implant bone. This contradiction is more pronounced in recently published review papers that fail to establish an argument that supports overloading as a causative or even, contributing factor for the loss of osseointegration, while others identify a possible or an obvious correlation between occlusal overload and peri-implant marginal loss in the absence of infection.

The theory that overload is a causative or, at least, a contributing factor to the loss of osseointegration is not new. Although authors attempted to give a definition to overload, no study describes the precise nature or magnitude of overload. Furthermore, in many publications, the terms “over-occlusion” and “overload” are considered to be identical. However, over-occlusion does not necessarily provoke loading forces with a nature and magnitude to cause bone loss.

Pellegrini et al in a recent review, investigated the histologic findings of bone structure around implants subjected to overload. The authors report that it is not possible to draw conclusions that could be applied in humans; however, gathering histologic data from the current literature that seem to support the evidence of the detrimental effect of overloading on the bone-implant interface, they suggest that clinicians follow surgical techniques and prosthetic solutions that relieve peri-implant bone from excessive stress. Clinical studies that show loss of peri-implant bone caused by overloading are lacking, as such tests in humans are inappropriate and unethical, and, generally, they are limited to case reports. However, in a clinical study, Trisi and Rebaudi evaluated by clinical follow-up and histologic analysis the peri-implant bone reaction during different therapeutic orthodontic conditions. Authors reported occasional presence of microcracks detected in dense cortical bone associated with a high remodeling rate and porosity of bone that could indicate overload.

In the present study, over-occlusion in the overloading group resulted in implant overloading of variable magnitude that ended up being either beneficial or detrimental to peri-implant bone. That is, overload induced either an increase in BIC, when strains came under the mild overload range, or bone resorption if strains were above the threshold, entering the pathologic overload range. This variation is justified by the fact that occlusal forces change by the location in the mouth and by the initial peri-implant bone density. This was observed even along the body of the same implant (Figs 7a and 7b) since pristine bone was of variable density, and according to a general mechanical principle, stress differs along an osseointegrated implant body. Data that loss of osseointegration may be caused by occlusal load were published by Isidor. Implants were placed in monkey mandibles; the prosthesis was mounted in supraocclusal contact with the antagonist teeth, which caused a lateral displacement of the mandible during occlusion. This loading environment resulted in loss of osseointegration in six out of eight implants. Two implants were lost.
due to loss of osseointegration along the entire implant body, while the other four had significant clinical mobility with little or no marginal bone loss. However, the remaining two implants exhibited high contact of mineralized bone with the implant surface. In a series of studies, Miyata et al. examined the influence of controlled occlusal overload on implants placed in the monkey mandible with no inflammation of peri-implant tissues. Implant crowns with mild supraocclusion of 100 μm caused no injury. However, significant marginal bone loss was detected when severe supraoclusion of more than 180 μm was implemented. Nagasawa et al. using a small animal model, reported loss of osseointegration around implants placed in the rat maxillae due to excessive occlusal load, in the absence of infection. Authors suggest that clinicians should be aware that implants may not be able to withstand overloading in cases where bone is not dense enough to tolerate occlusal forces.

On the contrary, Heitz-Mayfield et al. placed implants in dog mandibles and created supraocclusal contacts with antagonist teeth using gold crowns. They observed, during an 8-month overloading period, no loss of osseointegration or crestal bone loss in the presence of good mucosal health. Similar results were found by Kozlovsky et al., who put implants in dog mandibles and, after the osseointegration period, left them in axial supraocclusal loading for 12 months in the presence of uninfamed mucosa. The authors concluded that overloading increased the BIC percentage. Based on the same experimental design, Kan et al. investigated the biologic reaction of peri-implant bone in relation to the critical strain thresholds set by Frost’s “mechanostat” theory by enumerating peri-implant bone strain under quantified occlusal overload achieved by supraocclusal contacts. The authors reported that peri-implant bone strain values fell below the pathologic overload threshold of 3,000 με. However, strain was measured at a distance from the critical bone-implant interface where strain magnitude was dissipated. Furthermore, measurements were made on the cortical bone surface, while the whole experiment was performed in the dog mandible, where cortical bone predominates. It is not clear how strain threshold limits are related to bone density and how these limits alter according to bone density classification systems.

In the present study, 5 out of 16 implants of the overloading group lost osseointegration. However, the rest exhibited significantly higher BIC% in comparison to the unloaded controls. This result is in agreement with the study of Isidor in relation to the implants that remained osseointegrated as well as to the studies of Miyata et al., Heitz-Mayfield et al., and Kozlovsky et al., and enhances the opinion that when forces come under the mild overload range they have a positive effect on peri-implant bone.

Special attention should be given on the causes of loss of 5 out of 16 implants of the overloading group of the present study. This result is partially in agreement with the study of Isidor in which six out of eight implants were lost, but in contrast with the results of the studies performed by Miyata et al., Heitz-Mayfield et al., and Kozlovsky et al., where no implant lost osseointegration due to overloading. A first explanation could be that over-occlusion in these latter studies did not provoke forces and strains that entered the pathologic overload range. Another different parameter is the quality of bone. In the present study, all implants were inserted in the low-density posterior maxillary bone, while the studies of Heitz-Mayfield et al. and Kozlovsky et al. were performed on dog mandibles. A similar study has not been performed in the past in order to have comparability in the results. Nevertheless, test implants exhibited higher BIC% than the control implants. A third different concept concerns the occlusal force; a dog bites with a mean force of 256 N or more. Isidor and Miyata et al. used Macaca Fascicularis monkeys that bite with a mean force of 140 N, that is, half that of a dog. Finally, there is a difference in the direction of forces applied through the premature contacts. It is reported that lateral forces are more detrimental to the implant attachment apparatus than the axial forces. In the present study as well as in the studies of Isidor, Miyata et al., and Heitz-Mayfield et al., lateral occlusal load was exercised. On the contrary, Kozlovsky et al. used axial forces on the implant body. Toward the same direction, it should be considered that the temporomandibular joint of the dog mainly acts as a hinge joint and allows only a minimal degree of transverse movement of the mandible, which is not the case for humans or monkeys, a fact that may differentiate the characteristics of the forces applied.

The progressive loading plus overloading group exhibited the highest BIC% of all groups, which means that progressive loading had a cumulative effect on overloading. This is the rationale behind the design of the present study since, according to the literature, progressive loading should be able to increase bone mass around an osseointegrated implant, creating a better environment to withstand the forthcoming overloading forces. Studies have reported reduced success rates when implants are surrounded by poor-quality bone. The increase of peri-implant bone mass due to progressive loading reported in the present study, before the application of the mastication forces, may act as a shield against the potential detrimental effect of overloading forces.
In the overloading group as well as in the progressive loading plus overloading group, a significantly higher BIC% was recorded when each group was compared with the unloaded control group. However, no significant difference was detected between them. This observation supports the opinion that the increase of the BIC% is mainly due to the effect of the dynamic overloading forces. Speculation of the histologic images reveals a high remodeling rate of the bone around implants of the overloading and progressive loading plus overloading groups, while in the unloaded group, bone is not remodeled and has no functional pattern as an indication of a long-standing implant without being loaded.

The bone density BD-1 between all groups did not display significant differences. The observation that the bone density does not follow the increase of BIC% is common and observed in other studies20,21,36,44,96 marking the bone reaction to loading mainly at the bone-implant interface level during the experimental time period. This similarity between all groups was recorded for the bone density BD-2 measurements as well. In the first part of this study series, where only progressive loading was involved, higher BD-1 than BD-2 was reported in both unloaded and test groups.36 In the present study, BD-1 did not differ from BD-2 in all three groups, mainly due to the longer experimental period that let loading affect the most distal sites to implant threads and, for the unloaded control peri-implant bone, to complete the remodeling cycles and enter a quiescent phase.

Crestal bone resorption due to overloading is reported in many studies24,25,45,82 while others do not quote a significant difference with unloaded implants.14,20,44 This is due to differences in methodology but is mainly because over-occlusal forces do not in all cases result in evoking pathologic overloading of the surrounding bone.14,45 In the present study, crestal bone resorption was measured to be significantly lower in the overloading group (P = .006) and in the progressive loading plus overloading group (P = .004) when each group was compared with the unloaded control group. According to this result, loading that was exercised on the implants between the limits of this study helped in the preservation of peri-implant bone. Nevertheless, crestal bone resorption between the two test groups was not significantly different (P = .281), evincing that progressive static load seems not to have a contributory effect to this process.

Crestal bone resorption was also observed in the unloaded group, as in relative previous studies23,36 which may be related to an inflammatory reaction due to plaque accumulation, surgical trauma,97 or normal bone remodeling.98,99 A significant difference in the implant success rate was reported between the overloading (68.75%) and the progressive loading plus overloading groups (87.5%), which should be attributed to the application of the progressive loading that helped bone to grow denser and withstand the forthcoming forces from dynamic loading. This is supported by the histologic observation of fully dense bone along the entire surface of many implants of this group (Fig 7). This observation provides the clinical significance of application of progressive loading on implants placed in low-quality bone, prior to superstructure connection, as a measure of protection toward the forthcoming high forces of mastication.

In the present study, 8 out of 40 implants were lost. Five lost implants belonged to the same dog, which had implants of both the overloading and progressive loading plus overloading experimental groups and exhibited a low implant success rate (3 out of 8 implants, 37.50%). This specific animal had a very aggressive behavior, constantly biting the cage and the feeding vessels. This behavior became noticeable from the beginning of the study; however, it was decided not to exclude the animal from the study in order to examine what effect these excessive occlusal forces would have on the implants. Two explanations may be given for this impressive low success rate in this dog: the first is clusterization, which has been defined as the phenomenon according to which the occurrence of implant failures is not randomly distributed in a treated population, but multiple implant losses are likely to occur in specific high-risk individuals.100 However, at many sites around these failing implants, areas of osseointegration and dense bone may certainly be observed. Nevertheless, bone at these areas is under resorption as a histologic depiction of the impact of overloading. Therefore, the possibility that over-occlusal forces led to pathologic overload around many of the osseointegrated implants of this dog should not be excluded.

CONCLUSIONS

From the limited results of this study, it may be concluded that over-occlusal forces are not identical to overloading forces and may be translated to a wide range of bone strain, toward mild overloading and bone mass increase, or pathologic overloading, irreversible bone damage, and even loss of osseointegration. Below the threshold of pathologic overload, the higher the force, the higher the BIC%. Significant histologic changes in the peri-implant bone were mainly provoked by the dynamic forces of mastication. The application of controlled progressive orthodontic loading on osseointegrated implants preceding
overloading forces increased, but not significantly, BIC. However, clinically, progressive loading helped implants to better withstand the overloading forces.

ACKNOWLEDGMENTS

R.J. Lazzara is a consultant for Biomet 3i Implants. The remaining authors claim to have no financial interest, either directly or indirectly, in the products or information listed in the article. The authors wish to thank the company Biomet 3i for providing the implants and components for this study. This work is dedicated to the memory of Alexander Veis.

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