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Biological Response to Dental Implant Loading / Overloading. Implant Overloading: Empiricism or Science?

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SUMMARY

Dental implants have reported success rates of over 90 % over long periods of time. However failures still occur and seem to be unpredictable. One factor that is being increasingly considered in failure of dental implants is occlusal loading. The aim of this article is to review literature related to loading and overloading implants through masticatory and parafunctional activity, in order to attempt to clarify causality of overload as related to implant failure. Within the context of the published literature, the consensus on overloading of dental implants is still an unresolved issue. It can be concluded that more research is required to reach a clearer understanding on the relationship between overload and interfacial biomechanics.

Key words: dental, implant, overload

INTRODUCTION

Dental implants have become a significant aspect of tooth replacement in prosthodontic treatment [1, 2, 3]. High implant success rates of the order of 78-100 % have been published, with more than 15 years of observation time [4, 5, 6].

Despite these high success rates, complications and failures still occur [7, 8, 9, 10]. The causes of failure have been reviewed without mandating a specific one. Implant success is reported to depend on both biologic tissue (soft tissues and bone) response and mechanical components strength (implant components and superstructure). The soft tissue is more susceptible to invasion by bacteria, whereas bone may be more susceptible to loading, both having been implicated in bone loss around implants. However, a clear causal relationship of bone loss to microbiological and overload factors has not emerged. Overloading of dental implants during functional and parafunctional activity has been extensively discussed but a clear point of view has not emerged. The aim of this article is to review the literature related to loads and stresses on implants, in order clarify the relationship between overload and peri-implant bone loss both during bone healing after implantation and following the establishment of osseointegration. PubMed search was conducted using various keywords and the 'related article' feature. All articles up to December 2002 were reviewed; and weighted according to their scientific basis.

Early implant loading at the bone implant interface

· **Early or immediate loading**

Historically, the Brånemark protocol [1] favored a prolonged healing period, to allow stabilization of the bone interface prior to clinical function. Furthermore, it was suggested that early loading of the implant may induce micromotion, which could lead to fibrous tissue formation around the implant, and the subsequent implant loss [11, 12, 13, 14]. However, to date there is no definitive clinical documentation that relates early loading to early implant failure resulting from a tissue-supported interim prosthesis being worn over a recently placed dental implant.

Although micromotion been implicated for fibrous tissue formation around an implant [15, 16, 17, 18], it has also been reported that low frequency micromotion may stimulate bone growth [19, 20]. Wiskott and Belser [21] explained the relationship between bone formation and magnitude of micromotion as illustrated in Figure 1.

It is possible that ''excessive" micromotion during healing phase may be one causative agent for the failure of osseointegration [22, 23, 24]. Their findings suggest that, a range of tolerable micromotion exists of the order of 50-150 µm that may in fact be favorable for osseointegration [24].

The efficacy of early/ immediate loading dental implants has been studied in animals [25, 26, 27, 28, 29, 30]. A number of authors have reported that early or immediate loaded implants show a greater percentage of bone-to-implant contact and more mature cortical bone than delayed- loaded controls [25, 26, 27, 30].

Long term clinical reports appear to support the application of early/ immediate loading of dental implants [31, 32, 33, 34, 35, 36, 37, 38]. Short term clinical reports also show promising results with early and immediate loading of dental implants [39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61]. Furthermore, there seems to be sufficient evidence emerging to support a one-stage non-submerged protocol which can achieve success rates comparable to implants placed in a two-staged submerged procedure [39, 62, 63, 64, 65].

Thus, it would appear that a common factor between early loading and delayed loading of dental implants is the initial stability (micromotion) of the implant, implying that close apposition of bone at the time of implant placement may be the fundamental criterion in obtaining osseointegration. The factors that relate to implant stability include bone quality, quantity, surgical technique, and implant design, which may influence the timing of loading for each individual situation [66, 67].

· **Clinical evaluation of implant stability (micromotion)**

The traditional clinical methods for evaluating bone-implant relationship include radiographic evaluation [68], tapping the implant with a metallic instrument and assessing the emitted sound [69], stability measurement with the

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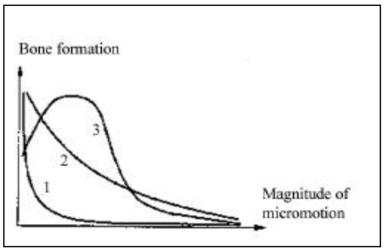

Figure 1. *Theoretical relationships between bone formation and magnitude of interfacial micromovement. (1) (i.e. complete immobilization) appears as unrealistic and disproved by available evidence on osseointegration. Pattern (2) is possible but indications are that some degree of micromovement is actually beneficial to osseointegration. (3) This latter pattern would match the proposed concept of stress that induces strain (i.e. deformation and micromovement) which in turn induces bone formation. (from Wiskott and Belser; 1999 [141], reprinted with permission).*

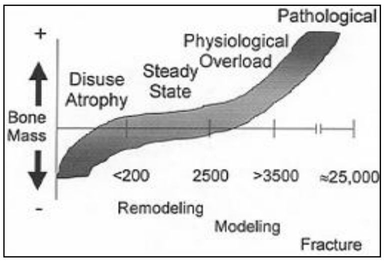

Figure 2. *Frost's mechanostat theory. Minimal effective strain (MES) of 50 to 250 μ-strain is necessary to prevent net loss in bone mass (disuse atrophy), whereas steady state level of normal remodeling exists from 50 to 250 and 2500 to 3500 μ-strain. Shaded area represents range of response in terms of change in bone mass. Peak load magnitudes creating strains above 2500 to 3500 μ-strain MES, lead to new bone formation (modeling) that continues until increased bone mass decreases strain values below modeling MES. Peak load levels >25,000 μ-strain lead to rapid catastrophic fracture. (from Stanford and Brand [125], reprinted with permission).*

Periotest instrument [70], and reverse torque application [71]. However, these methods are rather subjective and do not give a linear definition of the level of implant stability.

A recently developed apparatus (Osstell; Integration Diagnostics AB, Sweden) uses resonance frequency (i.e. tuning fork) to determine implant stability. The wave feed back is interpreted as a numerical value that is linearly related to the degree of micromotion of the implant [72]. This device may be able to detect changes in micromotion that could be associated with increase or decrease in osseointegration [73].

While it has been suggested that excessive micromotion (in excess of 150μm) during implant healing can induce connective tissue encapsulation, there is some evidence indicating that once the cause of instability is removed, the fibrous tissue may differentiate back into bone [14, 74, 75]. The use of Resonance Frequency Analysis (RFA) may provide a possibility to individualize implant treatment with regards to healing periods, detecting failing implants, type of prosthetic construction, and if one- or two-staged procedures should be used [66, 73, 76, 77, 78]. Although, short-term reports look promising, more long-term clinical reports would be required to confirm the reliability of this technique.

Summary

Initial close contact of bone to an implant (primary implant stability) may be one of the fundamental criteria for obtaining osseointegration and may permit immediate or early loading of the implant. However, more quantitative clinical methods must be established, to evaluate the condition of the bone-implant interface to provide a better basis for applying an immediate-loading protocol (such as maybe RFA).

Implant loading following II stage surgery

Late implant failures are those that occur following the establishment of osseointegration, usually considered 4-6 months post-insertion. The reasons for this type of failures have been considered to be overloading and/ or chronic bacterial infection (peri-implantitis) [79, 80]. Esposito et al [9] classified failures of Brånemark implants, according to the possible etiological factors. They found loading conditions in relation to bone quality and volume as major determinants in late implant failures for the Brånemark implants.

Overload in a biomechanical system may be defined as a condition where excessive chewing forces exert a repeated bending of the implant or mechanical components leading to marginal bone loss and/or mechanical failure [8]. Peri-implant marginal bone loss was/is considered as a sign of possible overload. Therefore estimation of peri-implant horizontal and vertical bone loss is an important parameter for evaluation and prognosis of implant success [81, 82]. Albrektsson et al [3] defined implant success as having less than 1.5 mm of marginal bone loss during the first year of loading and thereafter less than 0.2 mm. However, even if an implant is functioning over a certain period of time, the implant will eventually fail if the surrounding marginal bone level demonstrates a progressive resorption [83]. It has been suggested that bone loss be considered a complication only when a progressive excessive amount of bone loss is observed [84].

Factors that *may* affect the loading at the bone-implant interface

Although there is no direct link of the factors that may influence the bone-implant relationship, they are thought to include load-type, bone quality, parafunction-related, restorative factors, and implant design related factors.

a) Load related factors:

Occlusal loads, in general are classified as axial and non axial forces. Axial forces act perpendicular to the occlusal plane and are suggested to be more favorable as they distribute stress more evenly throughout an implant [85]. Non axial forces act in a non-perpendicular direction to the occlusal plane are thought to disrupt the bone-implant interface. This is supported by *in vitro* experiments, which show that non-axial loads cause stress concentration in the marginal area of the bone [86, 87, 88, 89] but, this has not been demonstrated *in vivo*.

There is one study [90], which showed evidence that non axial load disrupts the bone to implant interface. However, the magnitude of load generated was far beyond the range of clinical reality and implant failures occurred without preceding marginal bone loss, which would suggest a catastrophic failure of osseointegration. The few other studies investigating loading on the implant have not been able to demonstrate marginal bone resorption, induced by non-axial loading [91, 92, 93, 94, 95, 96]. The only failures that were reported of increased stress were of a mechanical nature [97, 98, 99].

Table 1. *Bone quality classification proposed by Lekholm and Zarb [101].*

Type 1	Homogenous compact bone
Type 2	Thick layer of compact bone surrounding a core of dense trabecular bone
Type 3	Thin layer of cortical bone surrounding a core of dense trabecular bone
Type 4	Thin layer of cortical bone surrounding a core of low-density trabecular bone

Summary

There appears to be no direct evidence that non-axial loading is harmful to osseointegration, but it may adversely affect the various components of an implant-supported prosthesis [100].

(b) Bone quality

The classification scheme for the bone quality proposed by Lekholm and Zarb [101] have been accepted by scientists and clinicians as the *de facto* standard in implant dentistry (Table 1).

Although higher failure rates have been reported for type 4 bone [102, 103, 104, 105], the more recent studies have failed to demonstrate any relationship between implant failure and type 4 bone [106, 107]. The contradiction of theses studies may be related to differences in implant implant surface treatments, loading conditions, and assessment of bone type.

Lindh et al [108] concluded from a meta-analysis that the success rates of machined surface implants were directly related to the implant length. Buser et al [109, 65] on the other hand found that with surface treated implants (i.e. Titanium Plasma Sprayed), good success rates (of >95 %) can be achieved with even short implants (6 mm). There appears to be some evidence to suggest that surface treatment may play a significant role in implant success.

Primary implant stability is determined by the bone quality and quantity, the implant design, and the surgical technique [110]. Controlling the variables of surgical technique and implant design, it is more difficult to gain primary implant stability in soft bone than in dense [111]. However, Friberg et al [112] using RFA method, demonstrated that implants placed in low density bone showed an increase in stability equaling that of implants placed in high density bone after eight months of bone healing. Conversely, implants placed in good quality bone showed only small increases in implant stability from the day of placement to the period of prosthesis placement (after 3-4 months) [73, 112]. These authors concluded that, if the bone quality/ density is high at the time of implant placement, the healing process may have little influence on future implant stability. This may well be the plausible explanation behind several authors experiencing good results with an immediate loading protocol in the anterior mandible [37, 38].

It would appear that implants placed in different bone densities eventually achieve similar stabilities, differing only in the time required to reach it [113]. This might indicate that longer healing periods might be necessary for implants placed in low-density bone [114]. It could also be interpreted that the threshold for tolerated micromotion is less in low density bone, which might vary according to implant design and implant surface topography [115]. Some authors suggest that a controlled progressive loading in low density bone may accelerate the modeling response to a formative state as suggested by Frost [116].

c) Parafunction related factors

Parafunction is defined as use of the masticatory system in a manner not related to speech and normal chewing. It may manifest itself as its dysfunction, wear on the natural or restored dentition, fracture of teeth, fracture of porcelain crowns, jaw pain or even combination of the above [117].

It has been suggested that parafunctional activity is a contraindication to dental implants, due to possible overload and subsequent failure [84, 103, 118, 119, 120]. In contrast, Engel et al [121]suggests that implants may provide protection of natural teeth and prostheses from effects of parafunction. Longitudinal studies have found no effect of occlusal wear or self reported tooth clenching (signs of parafunction) on bone loss around dental implants [122, 123, 124]. In these studies, some correlation of occlusal wear and bone loss was found in observation periods of 3 and 6 years. However, in re-evaluations after 10 and 15 years, no correlation was found. Engel et al [121] evaluated 379 patients wearing implant-retained or implant supported prostheses for many years, on the effect of bruxism on bone loss and implant stability. The study also gave no indication that implants in patients with occlusal wear had higher bone loss.

It appears that a clear relationship between parafunction and bone loss has not been established around dental implants. Perhaps, implants could be assigned a protective role to the remaining natural dentition.

(Restorative factors that affect the bone adaptation to loading will be discussed in Part II of the review.)

Bone adaptation to loading

Frost's mechanostat theory

Many theories have been proposed linking the bone adaptation to strain rate, energy density, history related factors, gradients, frequency and strain magnitude. Strain magnitude will serve as the foundation for this review as there appears to be more evidence implicating it in relation to loading.

Frost proposed that bone responds to a complex interaction of strain magnitude and time. As bone strains are typically very small, it is common to use the term μ-strain (10^{-6}). Conceptually the interfacial bone maturation, crestal bone loss and loading can be explained by the Frost mechanostat theory [116] which connects the two processes of modeling (new bone formation) and remodeling (continuous turnover of older bone without a net change in shape or size). In accordance with the theory, bone acts like a 'mechanostat', in that it brings about a biomechanical adaptation, corresponding to the external loading condition.

Frost described four micro-strain zones and related each zone to a mechanical adaptation (Figure 2). The four zones include the disuse atrophy, steady state, physiologic overload and pathologic overload zones. Both extreme zones (pathologic overload zone and disuse atrophy zone) are proposed to result in a decrease in bone volume. When peak strain magnitude fall below 50-200 μ-strain, disuse atrophy is proposed to occur, a phenomenon that is likely to explain ridge resorption after tooth loss. In the pathologic overload zone, peak stain magnitude of over 4000 μ-strain may result in net bone resorption. The steady state zone comprises the range between disuse atrophy and physiologic overload zone, and is associated with organized, highly mineralized lamellar bone. The stain magnitude

Table 2. *Summary of experimental studies relating bone loss to loading around dental implants.*

Authors (ref. no.)	Animal	Pattern of loading	Healing before loading
Isidor et al [90]	monkey mandible	Non-axial loading	6 months
Hoshaw et al [126]	dog tibia	Cyclical Axial loading	12 months
Miyata et al [127]	monkey mandible	Excess occlusal height of 100μm along with experimental inflammation	3 months
Miyata et al [128]	monkey mandible	Excess occlusal height	3 months
Duyck et al [129]	rabbit tibia	Excessive dynamic loading of 180μm and 250μm	6 weeks

Table 3. *Summary of experimental studies not relating bone loss from loading around dental implants.*

Authors (ref no.)	Animal	Pattern of loading	Healing before loading
Ogiso et al [132]	monkey maxilla and mandible	Supra-occlusion	4 months
Hurzeler et al [95]	monkey mandible	Repititive mechanical trauma along with ligature induced peri-implantitis	16 weeks
Miyata et al [133]	monkey mandible	Excess occlusal height	3 months
Asikainen et al [92]	sheep foreheads	Continous non-axial loading of 100µm	3 months and 3 weeks
Wehrbein et al [93]	dog maxilla	Continuous non-axial loading	8 weeks
Akin-Nergiz et al [94]	dog mandible	Continuous non-axial loading	12 weeks
De pauw et al [142]	dog zygomatic arch	Continuous non-axial loading	8 weeks

of 100-2000 µ-strain is thought to elicit this favorable bone reaction.

Physiologic overload zone covers the range between 2000 and 4000 µ strain, and is suggested to result in an increase in bone mass. The new bone formed is woven bone (immature bone) that is less mineralized, less organized and consequently weaker than the lamellar bone. It is probable that bone mass will continue to increase, until the bony interface accommodates these changes, and the load strain values then falls back into the range of steady state zone.

***In vivo* evidence on loading/ overloading of bone-implant interface:**

Experimental evidence correlating bone loss to overload (Table 2)

Isidor [90] created an uncontrolled overload state by placed the implants in supra-occlusion (in the non-axial rather than the axial direction) in monkeys, starting at about 8 months after implantation and continuing for 18 months. Five out of the 8 loaded implants failed between 4.5 to 15.5 months after initiation of loading. Isidor related this loss of osseointegration to 'fatigue microfractures in bone exceeding the repair potential.' The different pattern of uncontrolled loading may have exceeded the range of physiological range of bone adaptation.

Hoshaw et al [126] in a study using dogs, delayed loading of implants in the tibias for about 1 year and thereafter placed a 10-300 N cyclical load for 5 days. They reported significantly more crestal bone loss in the loaded group than in the unloaded group. Yet, it was not clear from this study if the crestal defect would have healed, had more time been allowed after the loading period. Also the data used for loading were derived from literature and not based on bone strength parameters of the animal concerned.

Both Isidor and Hoshaw studies demonstrated that loading beyond a certain threshold can be detrimental to the bone. However, both of these studies demonstrated different bone loss patterns. In the Isidor study, the implant failures were occurring without preceding marginal bone loss, while in the Hoshaw study, the bone loss was seen around the neck of implants.

In the second report by Miyata et al [127], a combination of occlusal overload and periodontal inflammation using ligature wires was induced. As the duration of loading caused by traumatic occlusion increased, bone resorption around the implants was observed. In the third report by the same group [128], bone responses around the implants induced by traumatic forces were investigated. Bone loss was observed when occlusal prematurities on the implant superstructure exceeded 180 µm. The authors recommended, not exceeding 100 µm of occlusal prematurity on an implant superstructure.

Duyck et al [129] to investigate the bone response to loads on implants, applied static and dynamic loads on 10 mm long implants (Brånemark System, Nobel Biocare, Sweden) installed bicortically in rabbit tibiae. They concluded from their study that application of dynamic loads, meeting the limits of the bone strength, causes crater shaped bone defects around the marginal part of the implant. Nevertheless, despite the crater shaped defects, the amount of bone in contact with the implant did not significantly change, thus suggesting a role of implant design in protecting the bone from excessive stresses and strains [130, 131].

Another interesting aspect of the study was that the healing period provided for these implants was 6 weeks (which is equivalent to 1 remodeling cycle in rabbits). It is plausible that bone was still undergoing maturation process, which could have affected the bone response to the specific loading conditions.

Experimental evidence not correlating bone loss to overload (Table 3)

Ogiso et al [132], in a study using monkeys, loaded implants by placing restorations in supraocclusion after osseointegration was established. Following an observation period of 1 month and 3 months, the histological analysis showed new dense bone formation around the implants, suggesting that osseointegrated implants can sustain high occlusal loading.

Hurzeler et al [95] evaluated in monkeys histologically the effect of a repetitive mechanical trauma alone on the peri-implant tissues, and the effect of a repetitive mechanical trauma in combination with ligature-induced peri-implantitis on the peri-implant tissues. Under the conditions of this study, the repetitive mechanical trauma showed no histologic effect on the peri-implant bone loss neither in healthy nor in diseased implant sites. Miyata et al [133], in their first report failed to find that controlled occlusal overload had an influence on bone loss around dental implants. The few other experimental studies also did not demonstrate marginal bone resorption, induced by non-axial loading [91, 92, 93, 94, 96, 142].

A small number of clinical studies have supported the hypothesis that marginal bone loss around dental implants may be associated with implant overload [84, 120, 122]. Longitudinal studies however, have found no effect of occlusal wear or self reported tooth clenching on bone loss around dental implants [122, 123, 124]. In their studies, some correlation of occlusal wear and bone loss was found in observation periods of 3 and 6 years. However, in re-evaluations after 10 and 15 years, no correlation was found, thus suggesting a role of time in bone stability. A literature review by Goodacre et al [10] concluded that for all studies analyzed, the mean marginal bone loss around dental implants ranged from 0.4 to 1.6 mm in the first year, and subsequent bone loss per year ranged from 0 to 0.2 mm.

Interestingly, some *in vivo* studies have demonstrated 'new bone formation' to certain loads [93, 134, 135, 136]. These studies support Frost's hypothesis [116], in that increasing strain may result in new bone formation. Most of these experimental studies reporting bone apposition have been done using orthodontic level forces on implants.

Time maybe a factor that should be considered, when studying the reaction of loading on bone-implant interface. In a 10 year follow-up study, Naert et al [137] demonstrated an increase in bone mineralization around implants over time. They reported 0.9 mm of bone loss at18 months [138], whereas 10 years later, bone level was measured at 0.45 mm suggesting a gain in bone level. Other clinical reports have also reported a gain of bone level over time [84, 103, 139, 140].

Osseointegrated implants may fail due to very high occlusal load under experimental conditions. However it still remains difficult to prove a direct relationship between overload and implant failure in humans. Besides, it is unclear, what the safe, and what the overload level is. It appears that the relationship between load and bone adaptation is governed by interactions of implant biomechanics over time, and strain magnitude maybe the one of the key determinants for stimulating the bone adapting response.

CONCLUSION

Primary implant stability between bone and implant may be the essential feature that permits the transfer of stress from the implant to the bone without any appreciable relative motion. More quantitative methods must be established clinically, to evaluate the condition of the bone-implant interface.

Under excessive loads, bone loss has been demonstrated in some animal studies. In human studies, where overload can be assumed to occur through parafunctional activity, bone loss from overload could not be demonstrated clearly. Bone gain over long term function has been reported by a number of studies, which suggests that functional loading over a certain physiologic range induces a positive bone reponse. This pattern supports the Frost's theory of bone adaptation to loading.

It can be concluded that more research is required to reach a better understanding on the relationship between overload and interfacial biomechanics.

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