

A Review of Dental Implant Treatment Planning and Implant Design Based on Bone Density

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Received: January 25, 2013; Accepted: March 14, 2013

Context: A key determinant for clinical success is the diagnosis of the bone density in a potential implant site. The percentage of bone-implant contact is related to bone density, and the axial stress contours around an implant are affected by the density of bone.

Evidence Acquisition: A number of reports have emphasized the importance of the quality of bone on the survival of dental implants. The volume and density of the recipient bone have also been shown to be determining criteria to establish proper treatment plans with adequate number of implants and sufficient surface area. Previous clinical reports that did not alter the protocol of treatment related to bone density had variable survival rates. To the contrary, altering the treatment plan to compensate for soft bone types has provided similar survival rates in all bone densities.

Results: When bone density decreases and bone become softer, the implant surface in contact with the bone decreases, therefore treatment plan should be modified by changing the drilling protocol, using gradual loading and reducing the force on the prosthesis or increasing the loading area with increasing implant number, implant position, implant size, implant design (deeper and more threads with more pitch, squared shape) and implant body surface condition.

Conclusions: Once the prosthetic option, key implant position, and patient force factors have been determined, the bone density in the implant sites should be evaluated to modify the treatment plan. Inappropriate implant number or design in poor quality bone results in higher failure rates. Changing the treatment plan and implant design is suggested, based on bone density to achieve higher survival rates.

Keywords: Bone Density; Dental Implant; Implant Design

1. Context

Available bone is particularly important in implant dentistry and describes the external architecture or volume of the edentulous area considered for implants. Previously, the available bone was the primary factor used to develop a treatment plan. Today, the treatment plan first considers the final prosthesis options. The patient force factors are then noted. The next consideration is the bone density in the site of the implants. The internal structure of bone is described in terms of quality or density, which reflects a number of biomechanical properties, such as strength and modulus of elasticity. The external and internal architecture of bone controls virtually every facet of the practice of implant dentistry. The density of available bone in an edentulous site is a determining factor in treatment planning, implant design, surgical approach, healing time, and initial progressive bone loading during prosthetic reconstruction (1, 2). In 1988, Misch proposed four bone density groups independent of the regions of

the jaws, based on macroscopic cortical and trabecular bone characteristics (1, 2). These four macroscopic structures of bone may be arranged from the least dense to the most dense. In combination, these four increasing macroscopic densities constitute four bone categories described by Misch (D1, D2, D3, D4) located in the edentulous areas of the maxilla and mandible. The bone density variance is dependent upon anatomical location and the local strain history of the bone after tooth loss. Generalizations for treatment planning can be made prudently, based on location. The bone density by location method is the first way the dentist can estimate the bone density in the implant sites to develop an initial treatment plan. It is safer to focus on the side of less dense bone during treatment planning. Therefore the initial treatment plan before computed tomographic (CT) radiographic scans or surgery suggests the anterior maxilla is treated as D3 bone, the posterior maxilla as D4 bone, the anterior

Implication for health policy/practice/research/medical education:

Providing the long-term survival rate and higher success rate of dental implant in poor bone quality/Ideal treatment planning based on making proper decisions; make a selection based on a scientific approach, rather than on advertising or marketing opinion.

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mandible as D2 bone, and the posterior mandible as D3 bone. A more accurate determination of bone density is made with computerized tomograms before surgery or tactilely during implant surgery. The most critical region of bone density is the crestal 7 to 10 mm of bone, as this is where most stresses are applied to an osteo-integrated bone-implant interface and determines the treatment plan protocol (3).

Four facts form the basis for treatment plan modification in function of the bone quality are: (a) each bone density has a different strength; (b) bone density affects the elastic modulus; (c) bone density differences result in different amounts of bone-implant contact percent; and (d) bone density differences result in a different stress-strain distribution at the implant-bone interface. Bone density is an implant treatment plan modifier in several ways- i.e. prosthetic factors, implant size, implant design, implant surface condition, implant number, and progressive loading need or method.

As the bone density decreases, the strength of the bone also decrease. To decrease the incidence of microfracture of the bone, the strain to the bone should be reduced. Strain is directly related to stress. Consequently, the stress to the implant system should also be reduced as the bone density decreases. One way to reduce the biomechanical loads on implants is prosthesis special design to decrease force. For example, cantilever length may be shortened or eliminated, narrower occlusal tables designed and offset loads minimized, all of which reduce the amount of load (4). Removable prosthesis (RP-4), rather than fixed prostheses, permits the patient to remove the restorations at night and reduce nocturnal para-functional forces. RP-5 prostheses permit the soft tissue to share the occlusal force and reduce the stress on the implants. Night guards and acrylic occlusal surfaces distribute and dissipate para-functional forces on an implant system. As the bone density decreases, these prosthetic factors become more important. The load on the implant may also be influenced by the direction of force to the implant body (5). A load directed along the long axis of the implant body decreases the amount of stress in the crestal bone region compared with an angled load. Therefore as the bone density decreases, axial loads on the implant body become more critical. Bone grafting or bone spreading to increase the width of bone and to better position the implant relative to the intended load is considered for soft bone types.

As a result, for decreasing the force to bone implant surface contact, following methods have been suggested:

- 1) Changing the prostheses design
- 2) Changing the force direction applied to implant
- 3) Increasing the functional contact surface (by increasing the number of implant, Implant length, Implant design, Implant surface condition)
- 4) Progressive loading

All of these methods are more important for soft bone with lower density. Therefore implant treatment plan

should be changed based on density of bone in implant site.

2. Evidence Acquisition

Nowadays, a number of reports have emphasized the importance of the quantity and quality of bone on the survival of dental implants. The volume and density of the recipient bone have also been shown to be determining criteria to establish proper treatment plans with adequate number of implants and sufficient surface area (1, 2). Inappropriate implant number or design in poor quality bone has resulted in higher failure rates (6-8). Early loading failure has been a frequently reported complication, especially in soft bone (9-13). Methods reported to decrease failures include the use of larger surface area implant, surface coatings, and progressive bone loading (2, 14). A patented process to design an implant to optimize the amount of strain to the recipient bone at the cellular level within ideal physiologic limits was begun in February 1994 by Bidez et al. (15). The mechanical properties of different bone densities were identified and correlated to Misch's four bone densities classification (1, 2, 16). A finite element analysis resulted in the development of four different implant designs, one for each type of bone quality observed in the jaws (17, 18). In a prospective literature of BioHorizons by Strong et al. designing an implant system that is based on bone quality, which includes four-implant design, has been investigated. The Biohorizons system philosophy is based upon the tent that to minimize strain at the implant-bone interface, the surface area needs to be optimized where the mechanical stresses are greatest and the bone quality (that is, strength) is poorest. As a result of patented optimization techniques, as much as 450%, 5 fold increase in functional surface area is obtained when compared with other implant designs currently available (19).

Functional surface area is defined as the portion of a root-form dental implant that is able to dissipate compressive and tensile loads to the bone (19). In this system, implants are identified by their diameter and coded D1, D2, D3 and D4 to reflect the bone density for which they are indicated. Their design specifically addresses the quality of bone and modifies the surface area in relation to the changes in strength and modulus of elasticity (17, 18). As a result, the surface is greater in softer bone, which generally occurs more often in the posterior regions, where the stresses are also highest. One implant length, based upon the bone density and implant diameter, is also pre-designed. For example, the 5 mm diameter implant for the densest bone (D1) is 9 mm long, whereas the D4 implant is 12 mm long. The 4 mm diameter implants are 1 mm longer than their 5 mm diameter counterparts. This is a report of 103 patients who have treated by 360 implants and 105 functional prostheses in a 12 to 26 month period, followed for three years. Furthermore this report investigates the effects of some parameters such as implant

design and bone density on survival and health quality of implant. This study suggests the bone quality based on dental implant design, minimizes overall implant failure and crestal bone loss, regardless of bone density.

Lekholm and Zarb (20) listed four bone qualities found in the anterior regions of the jawbone. Regardless of the different bone qualities, all bones were treated with the same implant design and standard surgical and prosthetic protocols. Following these protocols, Schnitman et al. (21) reported results with a 10% difference in implant survival between quality II and quality III, and as much as 22% implant failure in softer bone for the posterior maxilla. Engquist et al. (22) reported the loss of 38 of 191 implants in the maxilla in type IV bone (20% loss) and 8 out of 148 mandibular implants (5% loss) before stage II surgery with the Nobel Bio-Care implant. Jaffin and Berman (6) reported an overall 8.3% surgical and initial healing loss in 444 maxillary implants with softer bone with Nobel BioCare implants. Fugazzotto et al. (7) reported 22 failures out of 34 IMZ cylinder implants placed in quality IV bone, a 65% failure rate. A report from the Dental Implant Clinical Research Group (DICRG) (23) studying Paragon implants concluded that quality I bone had the highest surgical failure rate (4.3%), followed by quality IV (3.9%), quality II (2.9%), and quality III, which had the fewest failures (2.6%). The overall implant surgical failure was 3%; the maxilla had better survival at stage II surgery (98.1%) than the mandible (96.4%). In a study of BioHorizons by Misch (24) the overall surgical survival of the 975 BioHorizons Maestro dental implants from stage I to stage II in all bone densities is 99.4%. The combined survival rate from stage I implant insertion surgery to stage II uncover for D3 and D4 implants in soft bone is 99.6%. Therefore, the specific implant designs of one length and optimized thread design for each bone density have resulted in improved surgical survival. Another prospective study by Misch (25), which is based on two year research done on BioHoirzan system showed that Biohorizan Maestro implant system has been designed for bone micro strain during bone loading in physiologic region. This system help to improve different ranges of mechanical characteristics in any bone density. In this report, no implant failure occurred, and crestal bone loss values were similar to or less than values reported within the conditional two-stage approach. This may be related to the number and position of implants, implant design, and/or the surface condition of the implant loading. In a study by Freitas et al. (26), they showed that modified cutting thread which reduces bone microfracture, substantially increases initial stability even when torque values are less than 50 Ncm. This thread designed by Intra-Lock International Company is named "The Blossom Thread". This is a symmetrical helical tap built into the thread, which allows the bone to be cut efficiently rather than being sheared and microfractured it. By reducing insertion torque and compression to physiologic limits, this design significantly reduces the remodeling phase of the

bone, thus they do not see the initial drop in stability in 1-3 weeks that we see in traditional threaded implant designs. These results are independent of the type of bone they are placed into. In a three year beta test group they evaluated torque values in varying densities of bone. There was virtually no difference in cutting efficiency regardless of site. This would be significant advantage in soft bones, as light trabecular bones must remain intact to ensure initial stability. The treatment will be easier if the available bone is enough for desired prosthesis from aspects of number size and implant position. When the bone is not present, a modification of the treatment is necessary. These modifications include: (1) bone augmentation to fulfill the ideal treatment plan; (2) consideration of optional implant locations, usually with additional implants, or an increase in implant size; or (3) optimization of implant design. There are many different implant body designs available in implant dentistry. They may be categorized as a cylinder type, screw type, press fit, or a combination of features. Dental implants function to transfer loads to surrounding biological tissues. Thus the primary functional design objective is to manage (dissipate and distribute) biomechanical loads to optimize the implant-supported function. There are more than 90 dental implant body designs available. A biomechanical rationale of dental implant design may evaluate these designs as to their efficacy to manage biomechanical loads. Biomechanical load management is dependent on two factors: the character of the applied force and the functional surface area over which the load dissipated. Three types of forces may be imposed on dental implants within the oral environment: compression, tension, and shear. Bone is strongest when loaded in compression (27). An attempt should be made to limit shear forces on bone, because it is least resistant to fracture under these loading conditions. This is most important in regions of decreased bone density, because the strength of bone is also directly related to its density. An implant has a macroscopic body design and a microscopic component to implant design.

The microscopic features are most important during initial implant healing and the initial loading period. The macroscopic implant body design is most important during early loading and mature loading periods. Smooth-sided, cylindrical implants provide ease in surgical placement; however, the bone-implant interface is subject to significantly larger shear conditions. In contrast, a smooth-sided, cylindrical, tapered implant provides for a component of compressive load to be delivered to the bone-implant interface, depending on the degree of taper (28). The greater the taper, the greater the component of compressive load delivered to the interface. Unlike a cylinder implant, a tapered threaded implant serves no functional surface area advantage, because the threads of a screw bear the compressive loads to the bone. The lesser surface area of a tapered implant increases the amount of stress at the crestal portion, as demonstrated in three-

dimensional finite element studies (29). In addition, in a tapered threaded implant, threads at the apical half are often less deep, because the outer diameter continues to decrease. This limits the initial fixation of the implant. Different implant survival rates and amounts of marginal bone loss may be directly related to different implant body designs. The macro-design of an implant has an important bearing on the overall surface area to the load of the bone. Protruding elements of the implant surface, such as ridges, crests, teeth, ribs, or the edge of threads may act as stress transfers to the bone when load is applied. Threads are designed to maximize initial contact, enhance surface area, and facilitate dissipation of loads at the bone-implant interface (30). Functional surface area per unit length of the implant may be modified by varying three geometric thread parameters: thread pitch, thread shape, and thread depth (31). An improved functional surface area per unit length of the implant (in contrast to total surface area) is beneficial to reduce the mechanical stress to bone. Most stress to the implant-bone interface in D1 to D3 bone is in the crestal 5 to 9 mm of the implant; therefore the design of the implant body in the coronal 9 mm is most important to appropriately distribute occlusal stresses to the bone (29, 32, 33). Functional surface area also plays a major role in addressing the variable initial Bone-Implant Contact (BIC) zones related to bone density upon initial loading. D1 bone, the densest bone found in the jaws, is also the strongest, has the stiffest modulus of elasticity, and has the highest initial BIC percent, which approximates 80%. D2, D3, and D4 bone have progressively decreasing percentages of bone at the initial implant interface, with D4 bone ranging around 25% interface contact at the initial healing and uncover of a machined titanium implant (1, 2).

As a result, the implant geometric body design, length, and bone density are related to the functional surface area. For example, in more compromised bone sites (i.e. D4 bone), longer implants are required to resist off-axis and moment loads because of cantilevers, improper occlusion, or parafunction (34) D4 bone has the weakest biomechanical strength and the lowest BIC area to dissipate the load at the implant-bone interface. In addition, it should be considered that the functional surface area requirements would increase from a minimum for an implant in D1 bone to a maximum for implants in the D4 bone (35). D4 bone has the weakest biomechanical strength and the lowest BIC area to dissipate the load at the implant-bone interface. The functional surface area requirements would increase from a minimum for an implant in D1 bone to a maximum for implants in the D4 bone. Moreover, it should be noted that screw-type implants have more functional surface area, which is an advantage, especially in softer bone types. Implant body designs with threaded features have the ability to convert occlusal loads into more favorable compressive loads at the bone interface; therefore, thread shape is particularly important when considering long-term

load transfer to the surrounding bone interface. Under axial loads to an implant-bone interface, a buttress or square-shaped thread (typical of BioHorizons, Biolok, and Ankylosis) would transmit compressive forces to the bone. Under axial loads to a dental implant, a V-shape thread face angle (typical of implants from Zimmer, LifeCore, 3i, and some Nobel Biocare designs) is comparable to the reverse buttress thread (typical of some Noble BioCare designs) because of the similarity in the inferior portion of the thread face angle. A reduction in shear load and subsequent shear stresses at the thread-bone interface reduces the risk of bone failure and possible reduced bone-implant contact percent of the implant if all the other factors are equal, which is particularly important in compromised bone densities or shorter implant lengths (30). The thread shape (macroscopic design) is independent from the surface coating (microscopic design), is another important characteristic of overall thread geometry (30), which come in different shapes i.e. square, V-shape. Buttress, and reverse buttress. The V-thread design is primarily used for fixating metal parts together (34). The reverse buttress thread shape was initially designed for pullout loads. The force transfer for occlusal loads to the bone is similar to that of the V-thread design. The square or power thread provides an optimized surface area for intrusive, compressive load transmission. Most automobile jacks or engineering designs built to bear a load use some form of a square design. Yet, very few implant designs have incorporated a square thread design (BioHorizons, Ankylosis). A buttress thread shape may also load the bone with primarily a compressive load transfer (e.g. BioLok).

Based on Strong et al. maximum percentage of bone implant contact is observed in squared thread, then V shape and finally reverse thread. Occlusal loads in the axial direction of an implant body may be compressive at the bone interface when the implant body incorporates square or plateau designs, but can be converted to higher shear loads at the bone interface when the implant body incorporates V-shaped threads (30). The shear force on a V-thread face that is 30 degrees (typical of Zimmer Screw-Vent and Biomet 3i) is approximately 10 times greater than the shear force on a square thread (35). The shear component per unit length of a reverse buttress thread design is similar to a V-thread when subjected to an occlusal load. The reduction in shear loading at the thread-bone interface provides for more compressive load transfer, which is particularly important in compromised bone density, short implant lengths, or higher force magnitudes. The face angle of the implant body thread can modify the occlusal axial load to an angle bone implant load. A power thread (square) may load the bone interface in compression when an axial load is delivered to the implant crown. The square-thread design has a beneficial shape for occlusal loading compared with other thread designs (24, 31, 36). A

review of the literature suggests that the square thread implant design may provide similar success rates in the maxilla and mandible in a wide range of differences in bone density (31,37-39). Thread pitch is the distance measured parallel between adjacent thread form features of an implant (30). A decrease in the distance between threads will increase the number of threads-per-unit length. The implant pitch may be made smaller when the magnitude of the force is greater than usual (30). An implant with greater thread numbers may improve the functional surface area for the height dimension compromise (40). The thread pitch may be used to help resist the forces to bone with poorer quality (41). Because the softest bone types are 58% weaker than ideal bone quality, the implant thread number may be increased to magnify the overall surface area and reduce the amount of stress to the weaker bone trabeculae. Therefore, if force magnitude increases, implant length decreases, or bone density decreases, the thread pitch may be decreased to increase the thread number and the functional surface area. The greater the thread number, the greater the initial fixation and the overall surface area after loading.

The surgical ease of implant placement is related to thread number. The fewer the threads, the easier to insert the implant. If fewer threads are used in denser bone, the ease of placement is improved; because hard bone is more difficult to tap and insert a threaded implant. The thread depth is the distance between the major and minor diameter of the thread (30). In a tapered implant so the thread depth decreases toward the apical region. As a result, this implant design has overall less surface area, which is more critical in shorter implant lengths. Thread depth in BioHorzan square threaded implants are more than V shape thread of Biomet 3i, Zimmer, ITI, Nobel Replace, so that BioHorizon has maximum contact surface and NobleReplace has minimum contact surface. The greater the thread depth, the greater the surface area of the implant, if all other factors are equal. BioHorizons has the most surface area, contrary to NobelReplace, which has the least. The more shallow the thread depths, the easier it is to thread the implant in dense bone, and the less likely bone tapping is required prior to implant insertion. Because implant surgeons often decide what implant they will insert based on ease of surgical insertion, it is not unusual that an implant with fewer threads and less deep threads are selected, because both conditions facilitate insertion. However, after the implant is placed into the bone, the conditions that make implant surgical insertion easier create less functional surface area, and increase the risk of occlusal overload to the bone-implant interface. The thread depth may be modified relative to the diameter of the implant, and thereby the overall surface area may be increased by 150% for every 1-mm-diameter increase. Therefore the overall functional surface area of an implant body is related to the thread pitch, thread shape, and thread depth.

3. Results

Considerable effort should be made in the treatment plan to decrease the negative effects of compromised bone density, including implant size. The most important factor to decrease stress to the implant-bone interface is usually an increase in implant number, which dramatically increases the effective surface area over which the occlusal loads are dissipated, and in turn decreases stress. The next beneficial step to decrease the risk of overload is to increase the implant size. The size of an implant may be modified in either length or diameter. Increase in implant size is beneficial to decrease the stress applied to the system. The softer the bone, the greater the implant body length and diameter suggested.

Briefly, when bone density decreases implant surface should be increases with following methods:

- 1) Increasing of Implant number
- 2) Increasing of Implant diameter
- 3) Increasing of Implant length
- 4) Modifying of Implant design
- 5) Modifying of Implant surface condition

Long term stability of implant is related to surface area. Increasing the number of implants is the most efficient method to increase surface area and reduce overall stress. The surface area of the implant macrogeometry may be increased to decrease stress to the implant-bone interface (41, 42). The width of the implant may decrease stress by increasing the surface area (41, 43). Because the greatest stresses are concentrated at the crestal region of the implant, width is more significant than length for an implant design, once adequate length has been established. D4 bone should often require wider implants compared with D1 or D2 bone. This may require onlay grafts or bone spreading to increase the width of bone, when other stress factors are high. Based on long-term clinical experience of Vshaped threaded implant bodies, the minimum bone height for initial fixation and early loading for D1 bone is 7mm; for D2 bone, 9 mm; and for D3 bone, 12 mm using the classic V-thread screw implant design and titanium surface condition. D4 bone benefits from relatively longer implants for initial fixation and early loading compared with other bone densities, not only for initial fixation, but also because the stress/strain transfer of occlusal forces extends farther down the implant body. This implant length requirement may require sinus grafts in the posterior maxilla. The macro design affects the magnitude of stresses and their impact on the bone-implant interface (33, 44-46) and can dramatically change the amount and contour of the bone strains concentrated at the interface. Changing the implant design is suggested based on bone density. Different implant design criteria respond to different bone densities. Bone densities exhibit a tenfold difference in strength, and the elastic modulus is significantly different between D1 and D4. Implants designed for D4 bone should have the greatest surface area. For example, a classic V-thread

screw design has 30% more surface area than a cylinder implant. An implant body designed for the soft bone should have more and deeper threads than an implant body designed for hard bone. A DI implant, on the other hand, may be designed for easy surgical placement, as the strains under load are minimized, but the surgical failure rates are greater. Coatings or the surface condition on an implant body can increase the bone-implant contact percentage and therefore the functional surface area. Especially hydroxyapatite coating is suggested in D4 and result in improved short term survival rate. After 1 to 2 years, the mechanical load on the overall implant design is more critical to the amount and type of bone contact compared with the surface condition on the implant body. Rough surface conditions also may have some disadvantages. Plaque retention when exposed above the bone, contamination, and increased cost are a few of the concerns with roughened surfaces. The benefit and risk of surface conditions suggests the roughest surfaces are most often used in only softer bone types. Progressive bone loading provides gradual increase in occlusal loads, separated by a time interval to allow the bone to mature and accommodate to the local strain environment (2). Over time, progressive loading changes the amount and density of the implant bone contact. The increased density of bone at the implant interface improves the overall support system mechanism. The softer the bone, the more important the need for progressive loading (1, 2).

4. Conclusions

The density of the recipient bone have been shown to be determining criteria to establish proper treatment plans with adequate number of implants and sufficient surface area. Considerable effort should be made in the treatment plan to decrease the negative effects of compromised bone density. The results of this literature review showed that when bone density decreases and bone become softer (like D4), the implant surface contact to bone decreases, therefore treatment plan should be modified by considering the following issues:

Changing the drilling protocol, using gradual loading and reducing the force on the prosthesis or increasing the area of load by 1, increasing implant number; 2, implant position; 3, implant size; 4, implant design (deeper and more threads with more pitch, squared shape); 5, implant body surface condition. For a very dense bone, during the surgery process, implant should be designed, so that it can be implanted easily. Therefore less thread with V-shape structure and reverse buttress are more suitable. The implant body design is responsible for transmitting the occlusal stress of the prosthesis to the supporting bone. Therefore it is prudent to make a selection based on a scientific approach, rather than on advertising or marketing opinion. This decisions is even more important when bone density is poorer than usual.

Acknowledgements

The authors do not have any financial interests, either directly or indirectly, in the products listed in the study.

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