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# Some Biomechanistic Concerns on Newly Developed Implantable Materials

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## Abstract

Osseointegration and its strongly related stability of placed implants are very important in terms of their success and survival rates. Biomechanical compatibility is one of the crucial requirements for successful implantology among biological compatibility as well as macro- and micro-morphological compatibility. In this paper, we pay a special attention on newly developed implantable materials, which might cause a possible risk of implant failure due to a large mismatching with receiving vial bone in biomechanical environment.

**Keywords**: Biomechanical compatibility, Yield strength, Modulus of elasticity, Strain field continuity, Discrete stress field, Commercially Pure Titanium (CPT), Ti-based Alloys (TA), Zirconium Oxide (ZO) implant

## Introduction and Important Points to be Discussed

### Compatibility requirements

The implantation of devices for the maintenance or restoration of a body function imposes extraordinary requirements on the materials of construction. At least there are three major prerequisites for an implant system to be successful. The implant system is not necessarily limited to dental implants but it can refer to orthopedic implant systems including total knee or hip replacements. Three major required compatibilities for placed implants to exhibit biointegration to receiving hard tissue and biofucntionality thereafter should include (1) biological compatibility, (2) morphological compatibility, and (3) mechanical compatibility to receiving host tissues [1-3].

There are interactions between the foreign material and the surrounding host living tissue, fluid and blood elements. Some of these are simply adaptive. Others constitute hazard, both short and long term, to the survival of the living system [4,5]. Most of adaptive implantable materials show excellent corrosion resistance in vital environment, due mainly to forming passive oxide films [6]. Normally, materials exhibiting excellent corrosion resistance show good biological compatibility (in short, biocompatibility).

Surface plays a crucial role in biological interactions for four reasons. First, the surface of a biomaterial is the only part in contact with the bioenvironment. Second, the surface region of a biomaterial is almost always different in morphology and composition from the bulk. Differences arise from molecular rearrangement, surface reaction, and contamination. Third, for biomaterials that do not release nor leak biologically active or toxic substances, the characteristics of the surface govern the biological response. And fourth, some surface properties, such as topography, affect the mechanical stability of the implant/tissue interface [7,8]. In a scientific article [9], it was found that surface morphology of successful implants has an upper and lower limitations in average roughness (1 ~ 50μm) and average particle size (10 ~ 500m), regardless of types of implant materials (either metallic, ceramics, or polymeric materials). Accordingly, there are various surface modification methods and technologies proposed and practiced. They can be divided into two groups; one for surface concave roughening (in either macro- or micro-scale) method and the other for surface convex deposit-forming. All techniques reported so far should include, at least, as-lathed surface, titan plasma spray-coating, sand-blasted surface using alumina or titania fine particles, acid or alkaline chemical etching, sand-blasted followed by acid etching, anodic oxidation, laser abrasion, and anodic spark deposition [2,10]. Among these various surface

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modifications, there are two common outcomes; making surface layer be bioactive and higher wettability (in other words, unstable condition).

The third compatibility is the biomechanical compatibility as a main topic of this paper.

Biomechanics involved in implantology should include at least (1) the nature of the biting forces on the implants, (2) transferring of the biting forces to the interfacial tissues, and (3) the interfacial tissues reaction, biologically, to stress transfer conditions. Although, in orthopedic implants, bio-tribological factors (wear, friction, lubrication) as well as toxicity of the wear debris should be additional crucial elements in concerning successful implant therapy, it is beyond the scope of this paper; our following discussion is limited to dental implantology.

The requirements for above-mentioned three compatibilities should be satisfied to show the placed implants an excellent osseointegration.

### Stability and its related osseintegration

Implant stability plays a crucial role for successful osseointegration, which is a prerequisite for functional dental implants. Osseointegration is one of an important index to evaluate the success rates of dental implantation. The insufficiency of the osseointegration and increase of micro-motion can increase the failure risk of the implant at the early healing stage. Hence, osseointegration and implant stability are strongly related to each other [11-13]. Implant stability is established by two different stages: primary and secondary. Primary implant stability at placement is a mechanical engagement with cortical bone that is related to the local bone quality and quantity, the type of implant and placement technique employed. Secondary implant stability is developed from regeneration and remodeling of the bone and tissue around the implant after insertion and affected by the primary stability, bone formation and remodelling [14-17].

The role of biomechanical compatibility possesses its uniqueness and significance in differentiating itself from other two compatibilities (biological compatibility and morphological compatibility).

## Main Discussion

As mentioned previously, biomechanics involved in implantology should consider the nature of the biting forces on the implants, transferring of the biting forces to the interfacial tissues, and the interfacial tissues reaction, biologically, to stress transfer conditions. Interfacial stress transfer and interfacial biology represent more difficult and interrelated problems. Hence, many engineering variables such as implant shape, elastic modulus, extent of bonding between implant and bone etc., can affect the stress transfer conditions. The successful clinical results achieved with osseointegrated dental implants underscore the fact that such implants easily withstand considerable masticatory loads. In fact, one study showed that bite forces in patients with these implants were comparable to those in patients with natural dentitions. A critical aspect affecting the success or failure of an implant is the manner in which mechanical stresses are transferred from the implant to bone. It is essential that neither implant nor bone be stressed beyond the long-term fatigue capacity. It is also necessary to avoid any relative motion that can produce abrasion of the bone or progressive loosening of the implants. An osseointegrated implant provides a direct and relatively rigid connection of the implant to the bone. This is an advantage because it provides a durable interface without any substantial change in form or duration. There is a mismatch of the mechanical properties and mechanical impedance at the interface of Ti and bone that would be evident at ultrasonic frequencies, which could be detected during the stability evaluation. It is interesting to observe that, from a mechanical standpoint, the shock-absorbing action would be the same if the soft layer were present between the metal implant and the bone. In the natural tooth, the periodontum (periodontal membrane), which forms a shock-absorbing layer, is in this position between the tooth and jaw bone [18,19].

Referring to Figure 1, it is clearly understood that natural teeth and implants have different force transmission characteristics to bone. Compressive strains were induced around natural teeth and implants as a result of static axial loading, whereas combinations of compressive and tensile strains were observed during lateral dynamic loading. Strains around the natural tooth were significantly lower than the opposing implant and occluding implants in the contra-lateral side for most regions under all loading conditions. There was a general tendency for increased strains around the implant opposing natural tooth under higher loads and particularly under lateral dynamic loads [6,19]. It can also be pointed out that the most distinct difference between these two is the fact that the natural dentition has a periodontal membrane, functioning as a mechanical shock absorber, as well as a solid bonding between tooth root surface and surrounding tissue; whilst with the implant, there are osseointegration and functional ankylosis. By further biomechanistic view, with natural teeth, there are shock absorption mechanisms and stress distribution; on the other hand, with implant, the stress tends to be concentrated and increase in crestal bone. It is true to see that blood supply in natural teeth is much higher than that with implant systems.

By means of Finite Element Analysis Method (FEM), stress-distribution in bone around implants was calculated with and without stress-absorbing element [20]. A freestanding implant (i.e., single unit) and an implant connected with a natural tooth were simulated. It was reported that (i) for the freestanding implant, the variation in the Modulus Of Elasticity (MOE) of the stress-absorbing element had no effect on the stresses in bone; changing the shape of the stress-absorbing element had little effect on the stresses in cortical bone, and (ii) for the implant connected with a natural tooth, a more uniform stress was obtained around the implant with a low MOE of the stress-absorbing element. It was also found that the bone surrounding the natural tooth showed a decrease in the height of the peak stresses [20]. The stress distribution pattern clearly demonstrated a transfer of preload force from the screw to the implant during tightening. A preload of 75% of the yield strength of the abutment screw was not established using the recommended tightening torques. Using FEM, a torque of 32 N-cm applied to the abutment screws in the implant assemblies was studied in the presence of a coefficient of friction of 0.26, and resulted in a lower than optimum preload for the abutment screws. It was then mentioned that in order to reach the desired preload of 75% of the yield strength, using the 32 N-cm torque applied to the abutment screws in the implant

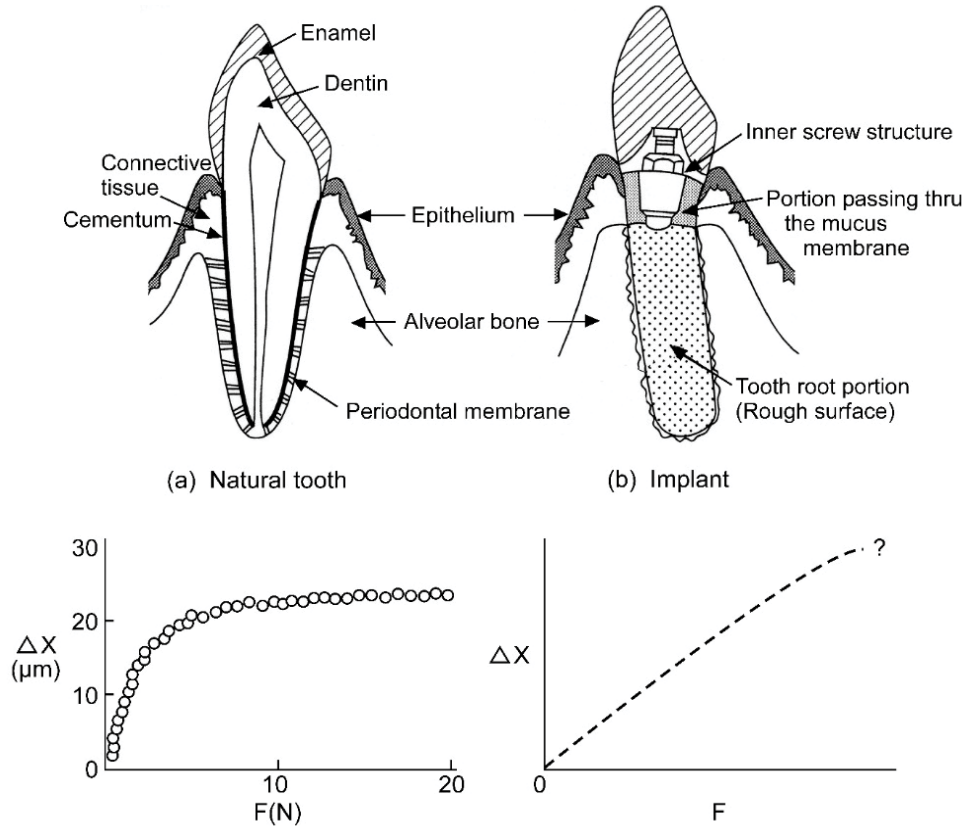


**Figure 1:** Schematic comparison between natural tooth and implant tooth.

assemblies studied, the coefficient of friction between the implant components should be 0.12 [21].

In addition to the aforementioned complicated mechanistic situation in implant/bone system, in long-term usage of placed implant (in particular, Titanium implant), there should be a risk for the hydrogen embrittlement [22] and high-cycle (low stress) fatigue weakening [23,24].

Having discussed on mechanistic environment around the osseointegrated implant and vital bone, it would be helpful to compare visually basic mechanical properties of these materials to understand the importance of mechanical mismatching, buffering effect, early and long-term stability of osseointegration by referring to (Figure 2). Figure 2 demonstrates yield strength versus modulus of elasticity (MOE) of various vital or non-vital materials which we can see intraorally; all are shown in log-log scale diagram.

First of all, bone (covering all types of 206 different bones in our body, occupying 12% of entire body weight) can be found about 100-200 MPa on yield strength and 10 to 20 GPa in MOE value. Commercially pure titanium (TI) and Ti-6Al-4V or Ti-6Al-7Nb alloy (TA) are found in stronger and more rigid zone, indicating that about one decade (in other words, 10 times higher) in both strength and rigidity.

There can be found a big gap between bone and Titanium materials (TI and TA). Even if, with this big gap, the initial

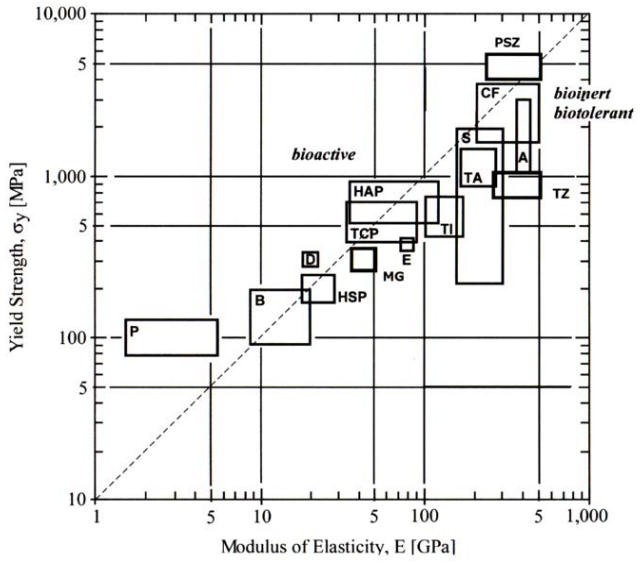


**Figure 2:** Stress-MOE relationship diagram of typical intraoral materials.
P: polymeric materials, B: bone, D: dentin, HSP: high strength polymers, MG: magnesium, HAP: hydroxyapatite, TCP: tricalcium phosphate, E: enamel, TI: commercially pure Titanium, TA: Ti-Al based alloys, TZ: Ti-Zr alloy, S: 18-8 series stainless steel, CF: carbon fiber, A: alumina ceramics, PSZ: partially stabilized zirconia ceramics.

ossointegration (or fusing vital bone tissue into surface zone of placed implant) were established, the interface at the surface zone should respond to the loading transmitting function. The placed implant and receiving tissues establish a unique stress-strain field. Between them, there should be an interfacial layer. During the loading with implant/bone couple, the strain-field continuity should be held (if not, it should indicate that implant is not fused to vital bone), although the stress-field is obviously in a discrete manner due to different values of modulus of elasticity (MOE) between host tissue and foreign implant material. Namely, stress at bone $\sigma_B = E_B\varepsilon_B$ and stress at implant $\sigma_I = E_I\varepsilon_I$. Under the continuous strain field, $\varepsilon_B = \varepsilon_I$. However $E_B \neq E_I$ due to dissimilar material couple condition. If the magnitude of the difference in MOE is large, then the interfacial stress, accordingly, could become so large that the placed implant system will face a risky failure or detachment situation. In other words, if interfacial stress due to stress difference $\Delta\sigma = (\sigma_I - \sigma_B)$ is larger than the osseointegrated fused implant retention strength, the placed implant will be failed.

Accordingly, there have been several ideas proposed and practiced. Hydroxyapatite coating onto titanium implant has been widely adopted since the both hydroxyapatite (HA) and receiving vital bone possess similar chemical compositions, hence early adaptation can be highly expected [25]. At the same time, $E_{HA}$ is positioned inbetween the values of $E_B$ and $E_I$ (see Figure 2); as a result, HA coating will have a second function for mechanical compatibility to make the stress a smooth transfer (or to minimize the interfacial stress). This is one of the typical hindsight, because HA-coating is originally and still now performing due to its similarity of its chemical composition to receiving bone - biointegration [25].

HA deposition is not only method to minimize the gap between bone and implant. Creating foam structure at the surface zone of implant material is effective alternative technique [26-28]. Since foam structure, depending on the extent of porosity and pore size thereof, exhibits its mechanical strength reduce down to 10-50% of those of solid structure [29,30], indicating that the original mechanical gap between bone and implant can be remarkably reduced.

Recently, two new implantable materials have been introduced; TiZr alloy [31-33] and zirconia ceramic [34,35]. The typical chemical composition of TiZr implantable alloy is Ti-15Zr-4Nb-4Ta [31] and exhibits mechanical property range is shown in Figure 2 as marked with TZ. Although mechanical strength of TZ appears to be similar to that of TA, TZ show higher MOE value than TA, possibly resulting in creating higher level of interfacial stress than the case of bone and TA as discussed previously.

Another new implantable material of zirconia is also seen in Figure 2, marked with PSZ. As seen clearly, PSZ possesses higher strength as well as rigidity, indicating that the risk of stress discrete situation between bone and zirconia should be the highest among any combinations foreseen from Figure 2. In addition, ceramic material is brittle, so that surface modification is not easily accomplished such as HA coating or foam-structure texturing.

As a conclusive note of the present short manuscript, it seems to be that research and development for implantable materials appears to be forwarding in opposite direction in viewpoint from biomechanical compatibility, which exhibits a strong responsibility to placed implant stability. It is hardly expected to strengthen the receiving hard tissue (bone) in prolong period of usage time of implant, rather it is natural to predict the bone be weaker and more fragile by aging of the patient. On the other hand, placed implant material should remain its original properties upon usage for, hopefully, a long time. Hence, the interfacial mechanical situation might be worsened, which is absolutely not a good prognosis for the implant receiving patients.

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