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Digital Engineering of Bio-Adaptable Dental Implants

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1. Introduction

Dental implants are the most integral part of modern dentistry (Brånemark, et al., 1969); they provide a permanent and effective solution for a wide range of dental complications and diseases (Tatum, 1988). The prominence of dental implantology is demonstrated by the increase of the number of dental implants used in the U.S. by ten folds from 1983 to 2002, leading to an increase in production capital from $19 million (1983) to $150 million (2002), with a projected yearly growth of 9.4% over the following few years (NIH, 1988; MRG, 2003) According to a report submitted by Merrill Lynch in 2007, the world dental industry is estimated around $2.2 billion (Jüngling, et al., 2006).

From a technological and clinical advancement stand-point, the field of dental implantology has rapidly expanded since its introduction in the late 60s' by Branemark (Spiekermann, et al., 1995). With the introduction of more complex and capable technologies in design, manufacturing, and testing, the dental implant converged to its dominant design of the three-piece assembly (rootform, abutment, and abutment screw) due to incremental changes driven by clinical research and feedback from patient monitoring and the attached trends of success and failure. The prominent design was also crystallized with an attached implant insertion protocol and corresponding pre- and post- implantation routines. The protocol includes biological, functional, and biomechanical assessments, which results into the formulation of different implantation factors such as implant position, amount of available alveolar bone, soft tissue biotype and morphology, implant design and material, abutment, and permanent crown (Sadan, et al., 2004; Poggio, et al., 2002; Touati, et al., 1999). An implantation requirement of great importance is the one devised by Brånemark and Breine et al. (1969), which suggests the countersinking of the implant below the level of crestal bone, while maintaining a soft tissue enclosure for 3-6 months, enforcing a non-loading period before a second-stage surgery would be required in order to uncover the implant and place the abutment and the permanent dental prosthesis. This loading prevention period was discussed in several subsequent studies, where it was concluded that the amount of motion provoked at the implant/alveolar bone interface in early stages of implantation strongly affects the implantations success. Pilliar et al. (1986) states that successful bone

integration is only possible in the case of micromotion, not macromotion, suggesting a threshold of 100 μm of micromotion would induce fibrous repair instead of osseointegration (Pilliar, 1991). A finding that was also discussed by Brunski et al. (1993) who considered that displacements of 150 μm to 500 μm are excessive micromotion that would disrupt the process of osteogenesis jeopardizing the implantation's success. Such thresholds prove to be dependent on surface and design characteristics; e.g. porosity (Szmuckler-Moncler, et al., 1998).

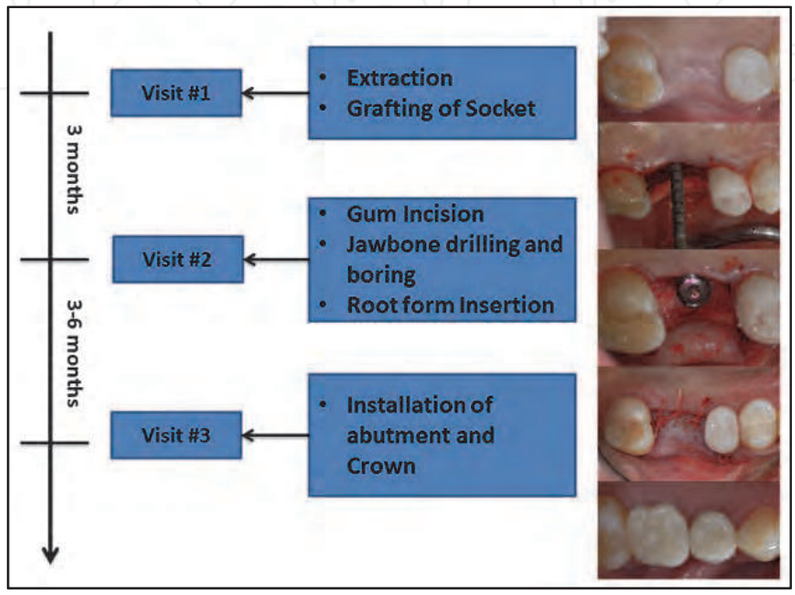


Fig. 1. Traditional post-extraction implantation protocol of a first molar

One area of traditional implantology that is of interest in the current Chapter is the replacement of a decaying unrepairable multi-root posterior dentition. While the survival rates of current implants can reach 95% (Buser, et al., 2002), this is only restricted to anterior single root dentitions. Fig. 1 exhibits a timeline of a traditional replacement of a first molar; it starts with an initial visit to the dentist, where the decaying dentition is extracted and the socket produced is packed with grafting material and enclosed for a healing period reaching 3 months. The second visit includes the surgical insertion of the implant, which is preceded by soft tissue incision, drilling, and boring of the jawbone in preparation of the insertion of the rootform. After insertion, the gum incision is enclosed in order to enforce the aforementioned non-loading period of 3-6 months. The third visit includes the discovery of the rootform and a subsequent installation of the abutment and the permanent dental prosthetic. In summary, the process spans over a period of 6-9 months costing three dentist visits, and a considerable period of incomplete esthetics or function.

In addition to the clinical complications that are imposed by the replacement of a decaying multi-root tooth, when comparing the dental implant to the organ in consideration (natural dentition), several discrepancies are eminent from the functional and physical perspective. In contrast to other load-bearing endosseous implants where a function is being replaced; e.g. hip joint replacement, or knee joint replacement a dental implant is replacing a complete organ which constitutes of a plurality of functions which drastically affect the well-being of a patient. One general discrepancy is the difference in micromotion provided by a dental implant, when

compared to natural teeth. A summary is portrayed in Table 1, extracted from (Misch, 2008), where a difference in functionality between natural dentition and dental implants is prominent due to a lack of initial movement (micromotion) in the latter.

Type of Movement	*Natural Tooth*	*Dental Implant*
Vertical Clinical Mobility	0 μm (Misch, 2008)	0 μm (Misch, 2008)
Initial Vertical Movement	28 μm (Parfitt, 1960)	2-3 μm (Sekine, et al., 1986)
Horizontal tooth mobility	56-108 μm (Rudd, et al., 1964)	<73 μm (Sekine, et al., 1986)

Table 1. Comparison of micromotion found in a natural tooth and a dental implant

Another important incongruity between a dentition and the device replacing it is the mismatch in elasticity between the biomaterial (Ti6Al4V 110 GPa (Collin, 1984)) and the surrounding alveolar bone (3-20 GPa (Abe et al., 1996)). A common complication in endosseous implants, the elasticity mismatch causes "stress shielding" which results in disuse bone atrophy manifesting in crestal bone loss in the case of dental implants and a higher risk of implant loosening (Vaillancourt, et al., 1996). In addition to a mismatch in mechanical properties, a mismatch in geometrical aspects is more pronounced in the case of posterior dentition. In a manual published by Zimmer Inc. (Zimmer Dental, n.d.), the average surface area of natural dentition was shown to vary from 154 mm^2 in the case of a mandibular central dentition, to 433 mm^2 in the case of a mandibular first molar. In contrast to a traditional implant that can reach a textured surface of only 310 mm^2.

The multi-component aspect of the traditional design of a dental implant provokes certain impediments that relate to three modes of deterioration which were investigated by Williams (1977): Stress Corrosion Cracking, Galvanic Corrosion, and fretting Corrosion. The latter is mostly pronounced at the abutment/rootform interface and it causes fatigue loading failure.

All the mentioned deviations in physical aspects and functionalities when comparing the modern dental implant to the organ that it replaces lead to a series of shortcomings which seems to be more pronounced in the case of posterior teeth; with the complex implantation surgery and the divergent functionality of the traditional medical device. Accordingly, a series of innovations were suggested over the past few years in order to overcome the mentioned shortcomings, while employing emerging technologies in design, data acquisition and manufacturing. Discussed in the next section, the prior art of new concepts of dental implants, which lead to the crystallization of the concept of bio-adaptable implant that is discussed in the current Chapter.

2. Prior art

Due to the different complications that aroused from traditional dental implantology, several alternative rationales were addressed along the years, which deal with shortcomings found in the function of dental implants, and the prescribed insertion protocol. Hodosh et al. (1969) introduced the concept of root-analogous implants, which enables insertion right after extraction. Some in-vivo testing proved root-analogous dental implant to provide some initial success, however portrayed poor success results (48%) 9 months after implantation (Kohal, et al., 1997), rendering the concept as unattractive. More recent work done by Pirker et al. (2008), employs CAD/CAM techniques to produce root-analogous zirconia implants with macro-retention on the surface. A main improvement is the reduction of the implant

size where it comes in contact with the brittle crestal bone, which was one main factors affecting the poor success rates of older versions of the concept.

Fig. 2 displays a few patents that provide alternative concepts of dental implants. Uckleman et al. (2004), introduced the use of laser-based additive manufacturing for the production of a customized abutment, which when coated produces the dental prosthesis. Hayashi et al. (2009), provided a similar concept of using additive manufacturing, where an abutment is produced on top of an abutment screw; hence, reducing the assembly of the implant to two components (in contrast to the traditional three-piece assembly). Rubbert et al. (2005) proposed the use of intraoral scanning for diagnostics and treatment pre-planning purposes, in addition to producing patient-specific dental devices. Mount et al. (2008), patented the concept of a root-mimicking dental implant that exhibits macro-retentions on the surface.

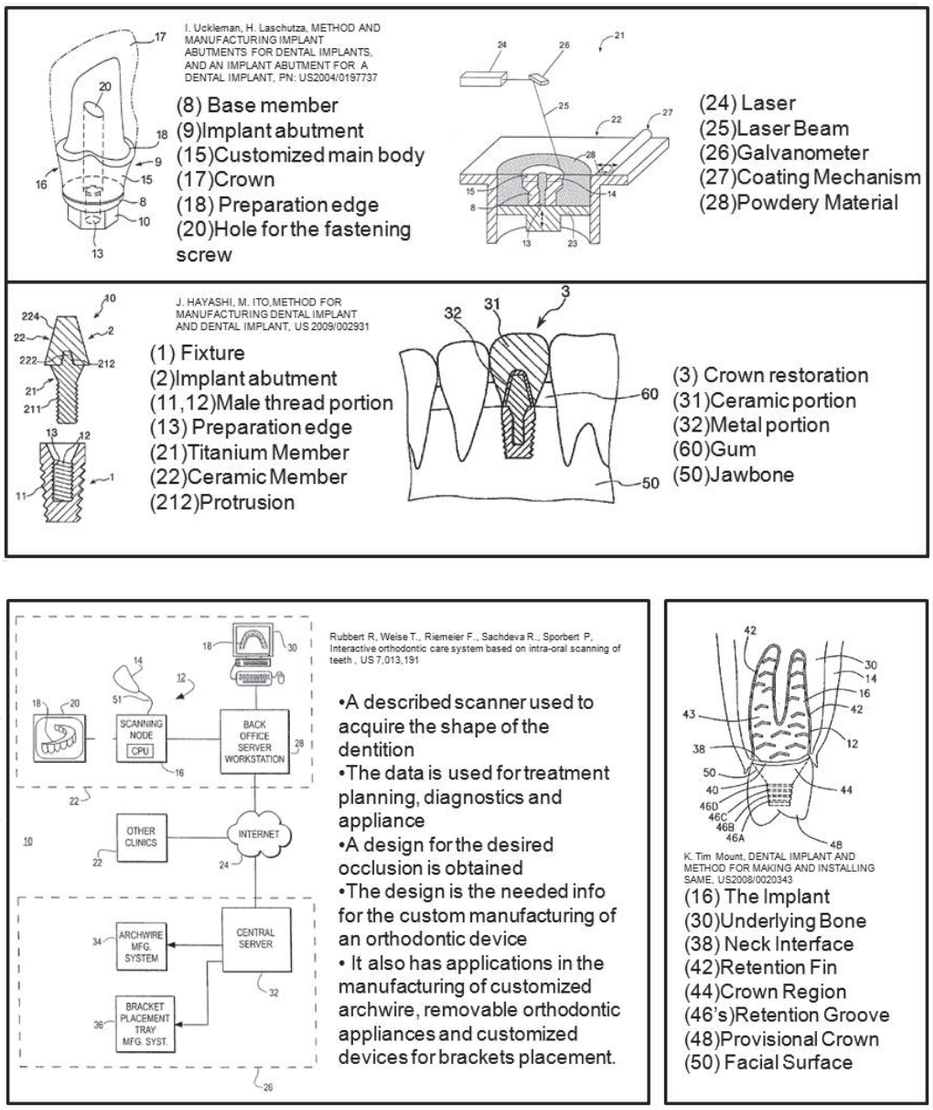


Fig. 2. Different dental implant rationales illustrated by their corresponding patents

An attractive design aspect, which provides a wide range of interest, is the use of porosity on the surface of the implant. In fact, porosity has been proven to improve clinical success by increasing the surface of the contact area (Geng, et al., 2001). In addition, a favorable osteo-blast reaction to the pores is also proven by (Xiropaidis, et al., 2005). One theory suggests that pores provide favorable mechanical conditions for bone growth, which was proven by finite element analysis (Cook, et al., 1982). In addition to porous coatings on the surface, dental implants that are built out of porous materials are also introduced by either additive manufacturing (Laoui, et al., 2006) or the by machining metal foams (NRC, 2005).
Dental implants with damping mechanisms also have been extensively addressed by several concepts, which are believed to provide better load transfer from the bite to the surrounding alveolar bone. Kraut et al. (1993), introduced intra-mobile damping, which employs polyoxymethylene connections, which is found in commercially available IMZ implants (Kanth, 1971; Kirsch, 1983). Patents provided by Ford (1999) and Wagher (1995) also introduced concepts of force distributing, and elastic implants respectively. Despite the several benefits expected from damping capabilities, the mobile aspect of the medical devices introduces failure concerns and maintenance requirement to ensure proper functioning.

3. Rationale of bio-adaptable dental implant

Singularities found in the biomedical field are as frequent as in any biological environment. Every patient has his own characteristics of jawbone density and geometrical aspects of teeth and surrounding biomass. The field of implantology has been limited to certain standards that were adopted due to design and manufacturing limitations. With the advent of digital engineering and its capabilities of designing and producing performance-specific customized parts in a time- and cost-efficient manner, the need of standardized sizes can be eliminated. In contrast of fitting patients' characteristics by means of intrusive and traumatic surgical practices, the implant can be tailored and customized to fit the patient in the least intrusive manner, maximizing benefits and minimizing healthcare cost, which has a positive impact on patient satisfaction and quality of life.
Digital engineering can be defined as the art of using extensive computational power to contribute and ameliorate endeavors in design, manufacturing, and testing. Accordingly, the field unrestrictedly includes: imaging technologies, image processing techniques, reverse engineering, additive manufacturing, and numerical simulation.
The work portrayed in the current chapter discusses the use of the various techniques that constitute digital engineering to design and manufacture a bio-adaptable dental implant that provides high levels of compliance to user-defined needs while abiding to design and functional constraints.

4. Concept

The concept of bio-adaptable dental implants was initially introduced as a customized root-mimicking dental implant (Chahine, et al., 2008; Chahine, et al., 2010). By taking advantage of modern computed tomography (CT) techniques and the subsequent analysis capabilities of the scan data and the generation of three-dimensional computer models, in addition to additive manufacturing (AM) and its ability of producing application-specific parts, a cost and time effective track of designing and producing customized dental implants was devised. A more elaborate approach is discussed in the current section, where the ability of AM to produce highly complex structures is taken to its full extent.

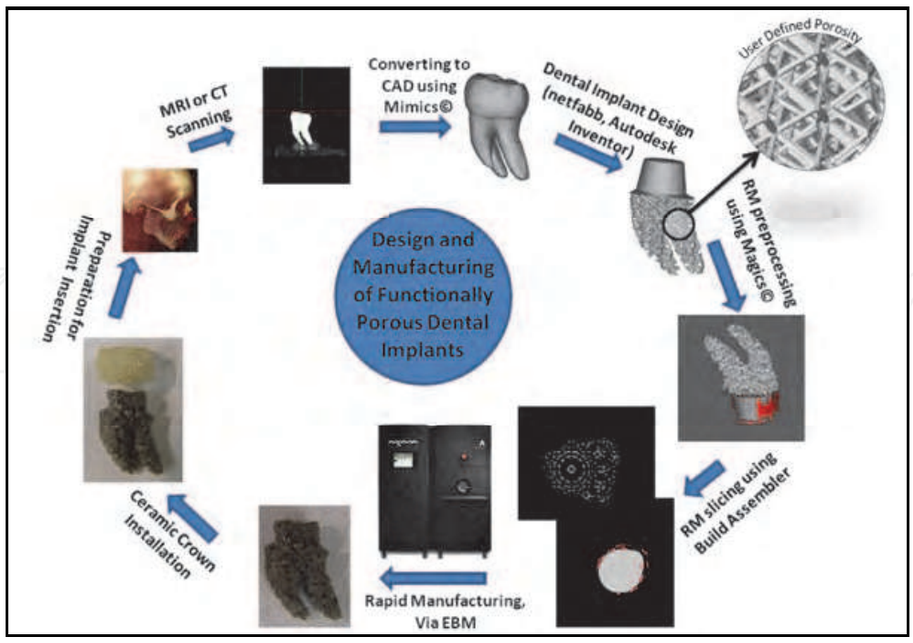


Fig. 3. Design and production of a bio-adaptable dental implant

The main application of the current concept deals with treating decaying posterior teeth by means of immediate implantation after extraction. Fig. 3 displays the design and manufacturing track of a bio-adaptable dental implant. A CT scan of a patient's dentition to be replaced is sufficient to provide enough geometrical data to produce a CAD model of the organ. The model is subsequently used to generate a root-mimicking design along with two main design characteristics: functionally graded porosity (FGP) and advanced abutment design (AAD) which will be discussed in more detail in a subsequent section. The design is then prepared for AM and manufactured. The implant undergoes post-manufacturing processing steps before being sent to the dentist's office before extraction. The lead-time of the entire process is in the range of 24 to 48 hours, enabling the production of the medical device in a time- and cost-efficient manner. Fig. 4 devises the concept of a service center for dental implants, where a the need of several dental clinics treating several patients' needs can be addressed by a single service center by bundling all the different patient-specific dental implants in the building envelope of an AM machine. The development of specialized software to generate bio-adaptable dental implant designs complying with patients' specifics can drastically reduce the already short lead time.

From a clinical concept point of view, the insertion protocol of a bio-adaptable dental implant provides several advantages when compared to the traditional approach. As displayed in Fig. 5, the implantation is executed in one dental visit in contrast to the three-visit protocol discussed earlier. The bio-adaptable implant is customized according to every patient and clinical situation; resultantly it provides optimal function and superior esthetics when compared to stock manufactured implants. In the case where CT scan banks are available, the implant can be ready upon the initial dental visit of the patient where the dentist can atraumatically remove the damaged tooth and insert the implant with minimal to no site preparation. Minimizing trauma will provide with faster healing of the surrounding bone (Misch, et al., 2005). In addition, the immediate placement can provide immediate esthetics and function.

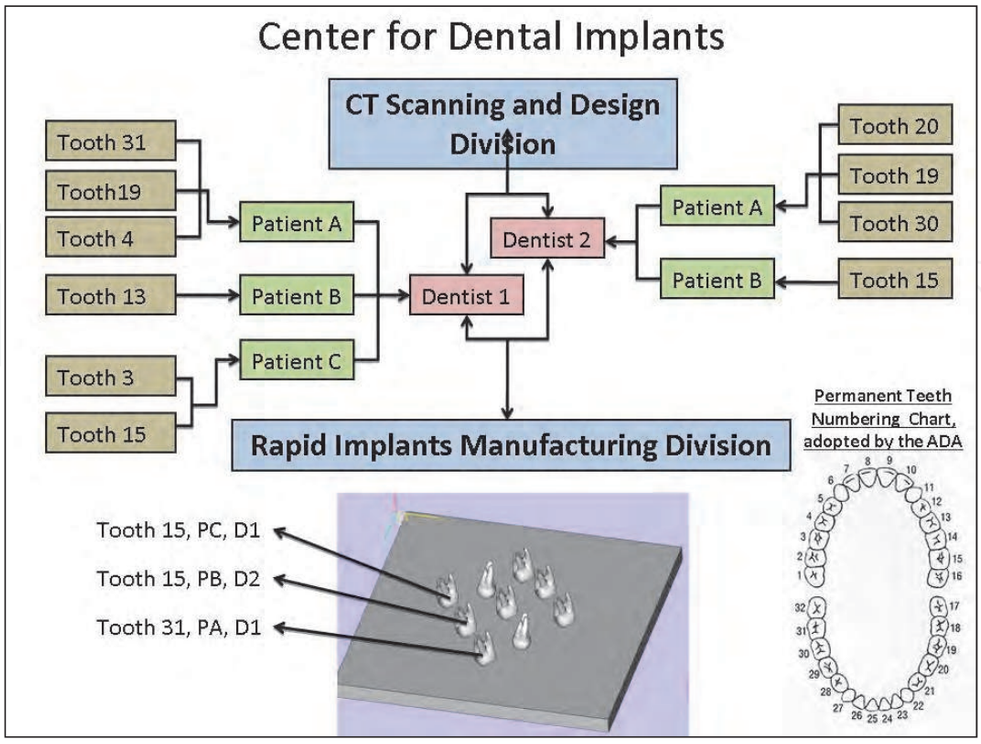


Fig. 4. Mass production Concept of a bio-adaptable dental implant

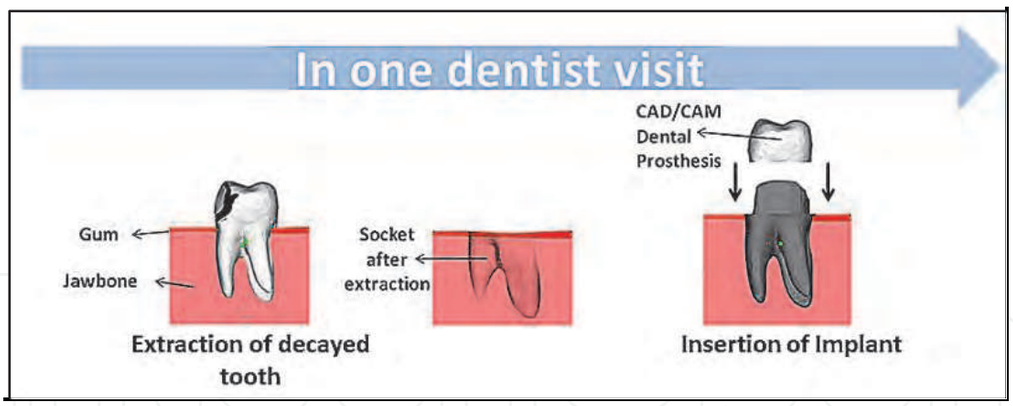


Fig. 5. Clinical concept of a bio-adaptable dental implant as a root-mimicking concept

5. Design and functionality

With the advent of scan analysis techniques and software, surgical pre-planning offers surgeons the ability to visualize and predict the surgical outcome (Stocker, et al., 1992). By analyzing the imaging data obtained from computed tomography (CT) or magnetic resonance imaging (MRI), geometrical models of different organs can be generated and used for a wide range of potential numerical simulation of thermal, bi-mechanical, and biological response. Fig. 6 displays a partial geometry of a patient's jaw that was extracted by CT scan analysis using Mimics®, software developed by Materialise (Leuven, Belgium), where

grayscale analysis is employed at every image to separate the different biomaterials (cortical bone, alveolar bone, dentition, periodontal ligament) and produce CAD models of the different bio-components. The first mandibular model displayed in the aforementioned Figure is designated as the dentition to be replaced. Accordingly it is used as the geometrical reference to which a bio-adaptable dental implant would comply.

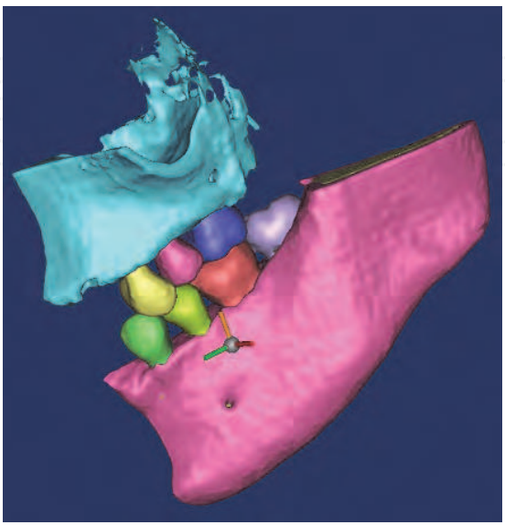


Fig. 6. Geometry of a patient's partial jaw extracted by means of CT analysis

In addition to detecting the geometry of various elements of the bio-environment, grayscale analysis also enables the detection of the anisotropic material properties of the different components. By mapping the grayscale distribution within a component, a distribution of the local material properties can be generated; e.g. elasticity and density. This contributes to a more realistic representation of the domain of interest.

As mentioned earlier, the main functional discrepancy between a dental implant and a dentition is the lack of micromotion, which is also referred to as initial movement. The main reason for the difference is the absence of a periodontal ligament at the implant/bone interface, which surrounds a natural dentition. Actually, a successful implantation is closely dependent on the osseointegration of the surrounding bone, and its mechanical and functional adhesion to the alloplastic material; i.e. the biomaterial. Despite a successful initial retention which can be enforced by macro-topologies at the surface, a long term implantation requires a successful bone reaction on the micro-level. Due to the direct bonding between the rootform area and the surrounding bone, the only approach that can enable crown movement in different directions involves imposing an elastic connection between the dental prosthesis and the anchored rootform.

Fig. 7 displays a preliminary design concept where either a fully porous abutment or an elastic interface can be designed in order to provide the relative micromotion of the crown. A more elaborate concept is shown in Fig. 8, where a thin featured abutment might provide enough flexing to induce micromotion. In contrast to intra-mobile dental implants that are commercially available, the current design approach deviates from the multi-component assembly and converges towards a one-piece dental implant which provides a wide set of functionalities which are provided by locally varying the mechanical properties of the implant.

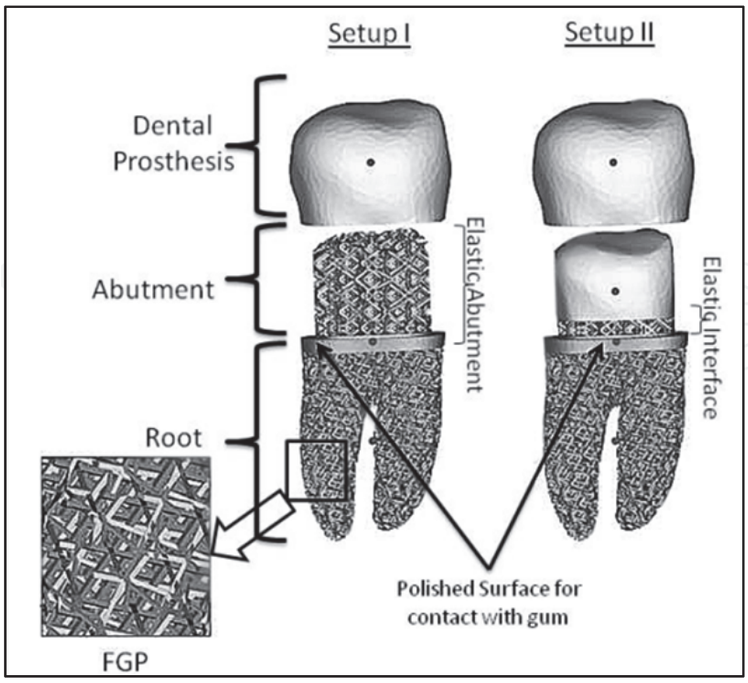


Fig. 7. Rendering of the FGP and AAD design aspects of a bio-adaptable dental implant

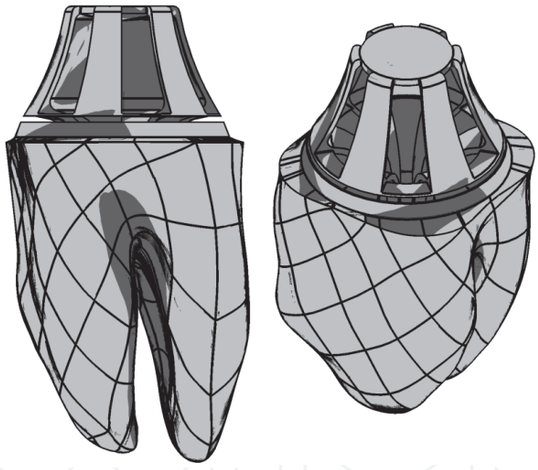


Fig. 8. A rendering of an AAD example

Fig. 9 displays a design example where the abutment rests on an elastic interface that exhibits a porosity corresponding to a desired elasticity. Under loading, the crown will exhibit more elastic behavior in contrast to the conventional case where it is directly anchored to the implant body.

One complication that can be imposed by the current approach of having open gaps in the abutment area is the risk of bacterial infection. A proposed solution involves injecting the cavity by medical polyethylene terephthalate, commonly known by the commercial brand Dacron® which is used in heart valves and internal sutures (Metzger, n.d.). Other candidate materials include medical silicone and polyoxymethylene.

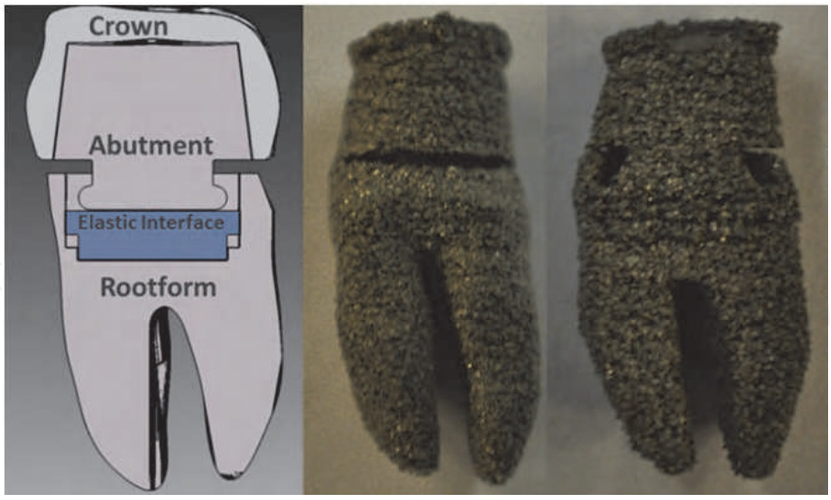


Fig. 9. Bio-adaptable dental implant with AAD (left), built by EBM® (middle), cross-section of the build (right)

The micromotion provided by the AAD, contributes towards a more natural function of the implant, rendering it an improved tooth-replacement. It promotes a more natural bite feel, and an enhanced interaction with the surrounding teeth. In addition, it enables the implementation of fixed bridging supported by a combination of an implant and a tooth, which is traditionally endangered by the discrepancy of the amount of micromotion exhibited by the tooth and the implant. However, perhaps the most prominent advantage of the AAD is minimizing the amount of micromotion transferred from the bite load to the connecting interface between the implant and the surrounding bone, especially in the early stages of implantation where excessive micromotion at the rootform leads to fibrous encapsulation.

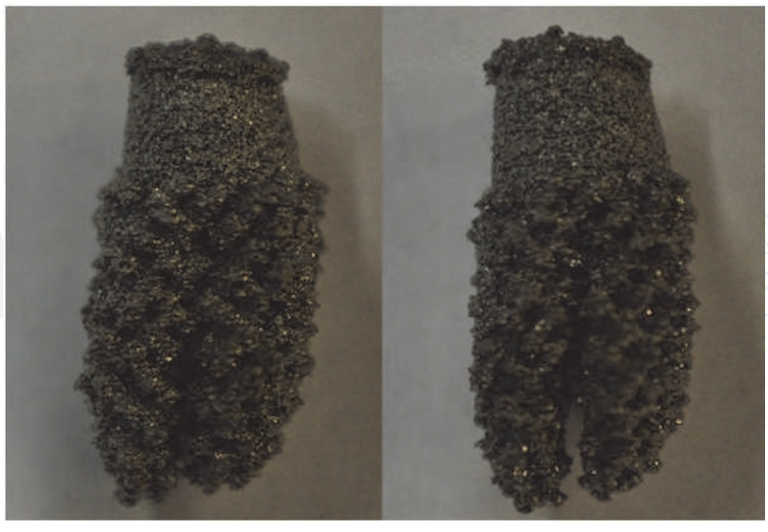


Fig. 10. Two bio-adaptable dental implants with porous rootform built by EBM®

FGP deals with locally varying the geometrical aspects of porosity, inducing locally varying mechanical, physical, and biological properties. FGP is applied at the rootform area of a bio-adaptable dental implant (See Fig. 10) provoking two levels of bone response: a macro-level,

and a micro-level. The latter relates to the reaction of bone cells to the micro-topology of the implant's surface. According to Hulbert et al. (1970), a 100 μm pore induces bone ingrowth, while a pore that is larger than 150 μm leads to an osteon formation. Work done by Simmons et al. (1999) discusses how mineralization rates are higher in porous surface when compared to a plasma sprayed texture, which is related to a favorable localized mechanical conditions in the pores. FEM analysis conducted by the same group (Simmons, et al., 2001) proves less severe volumetric and distortional tissue strains at the pores located at the interface of the implant, which provided favorable bone mineralization conditions according to Carter's tissue differentiation law (Carter, et al., 1998). Consequently, a porous surface contributes towards a biological union between the implant and the surrounding bone, leading to a longer lasting and stronger fixation. In fact, studies have shown that metal implants with a rough surface require a larger removal torque when compared to polished implants (Cohen, 1961).

The macro-level of bone response relates to the effect of osseointegration due to the stress induced in the bone. One main function of dental implant is to ensure the compressive bite-load transfer to the surrounding bone, which contributes to maintaining healthy bone levels in the jaw, in contrast to dentures which lead to alveolar ridge resorption. The optimal range of stress in the surrounding bone can be enforced by the development of FGP compliant to the loading conditions and the mechanical properties of the surrounding biomass.

Finally, one important function promoted by the bio-adaptable implant is the preservation of the stress pattern in the surrounding bone, due to the geometrical mimicking of the root of the initial dentition. This fact also reduces the need for orientation adjustments, due to the inert orientation provided by the socket, which otherwise would be calculated by the dentist and provided by a drill guide in the case of traditional implantation.

6. FEM as a design tool

Finite element method (FEM) is a numerical simulation which is used to solve problems in the physical domains of solid mechanics, heat transfer, fluid dynamics, and electromagnetism. Its main functioning deals with solving discretized equations that govern thermal, mechanical, and flow phenomena. During the 1970's, when FEM was initially introduced, it was mostly used in the aerospace industry. Since then, the fields of application have been drastically expanded.

Overviews provided by DeTolla et al. (2000) and Geng et al. (2001) discuss the application of FEM in the field of dental implantology. Compared to in-vivo and in-vitro testing, FEM provides a cost and time effective solution to predicting the clinical outcome of an implantation that is governed by specific variables. Extensive FEM work can be found in the literature that covers the effect of placement and inclination (Akça, et al., 2001; Canay, et al., 1996; Watanabe, et al., 2003), thread design (Eraslan, et al., 2010), implant dimensions (Himmlová, et al., 2004; İplikçioğlu, et al., 2002), occlusal loading position (Eskitascioglu, et al., 2004), and biomaterial (Stegaroiu, et al., 1998) on the surrounding biomasses and organs; i.e. jawbone, periodontal ligament, and neighboring dentition (Ishigaki, et al., 2003; Nagasao, et al., 2002; Nagasao, et al., 2003; Borchers, et al., 1983; Widera, et al., 1976; Akpinar, et al., 2000).

The main approach of implementing FEM into the design of a bio-adaptable dental implant, deals with tailoring the mechanical properties of different elements of the medical device, in order to comply with certain conditions and constraints that are imposed by the implantation. An example is displayed and discussed in the current section.

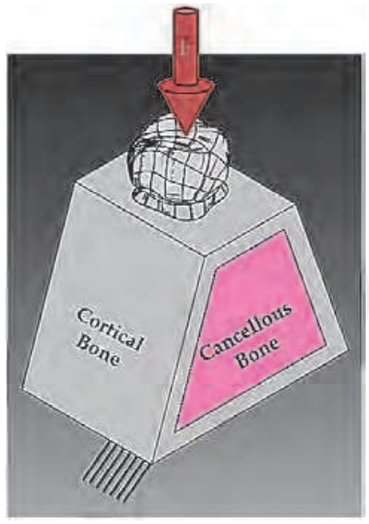


Fig. 11. FEM model, load, and constraints of a bio-adaptable dental implant

The schematic of Figure 11 displays a geometrical model that constitutes of a bio-adaptable dental implant with a solid rootform and elastic interface (See Figure 9) and the surrounding bio-elements; cortical bone, and cancellous bone. The bottom surface is constrained, while a vertical bite load is being applied on the implant. ANSYS® Workbench is used to solve for the stress and strain distribution along the geometrical domain. By employing the DesignXplorer® module provided by the software, the range of different outcomes can be evaluated, depending on user-set variable inputs. In this example the elasticity of the elastic layer is varied between 1-50 GPa, with a bite load ranging from 50-500 N. The plotted outcome is the maximum occlusal displacement of the crown, which related to the micromotion expected to be achieved by implementing AAD in a bio-adaptable dental implant. Figure 12 displays a 3D distribution of the micromotion vs. the two aforementioned inputs. As expected, a lower elasticity and higher bite load produce a higher level of micromotion in the occlusal direction. The range of micromotion that is produced by different combinations of inputs spans from 0.66 to 45.7 microns.
Referring to Table 1, a vertical initial movement of a natural tooth is 28 μm. By evaluating the patient's bite load range, an optimal elasticity of the elastic interface can be selected providing a range of micromotion analogous to that of a natural tooth.

7. Conclusion

The current chapter displayed a detailed description of the novel concept of bio-adaptable dental implants, and the expected clinical and functional advantages that it provides. It employs numerical information obtained from CT scans to produce an implant that provides maximum compliance to patient-specific geometrical and biomechanical constraints, while producing optimized functionality. Design aspects, such as FGP and AAD that display a local tailoring of mechanical properties, take full advantage of additive manufacturing's capability of producing parts with complex geometries. Potential advantages provided by the new concept include:

- Immediate restoration of function and esthetics
- Reduced treatment time
- No to minimally invasive site preparation

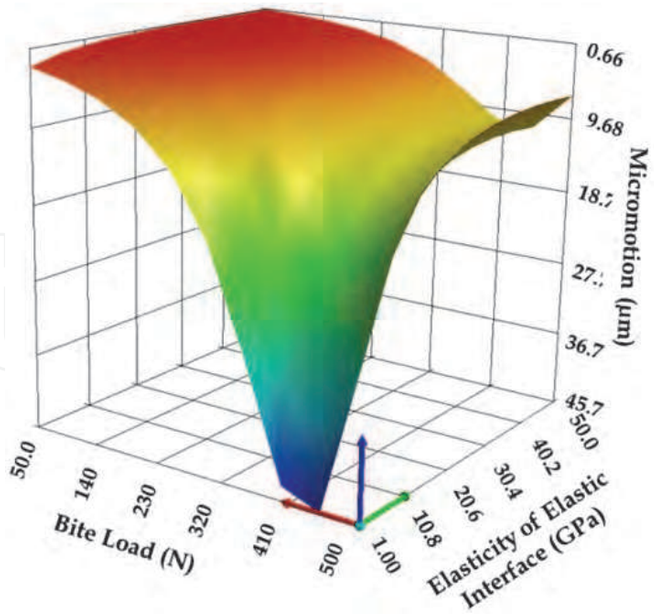


Fig. 12. DOE result of the maximum amount of occlusal micromotion produced by various levels of bite loads and elasticity of the elastic interface

- Better bite feel due to micromotion capabilities
- Enhanced bone response
- Improved patient satisfaction, and quality of life
- Reduced health care cost

The work portrayed discusses a new direction in implantology, where the implant matches the patient, instead of the contrary. This is only possible due to the advent of digital engineering, and the ability of producing customized medical device in a cost and time efficient manner, rendering it economically attractive.

Future work includes in-vivo testing of bio-adaptable dental implants, which depending on the preliminary findings might lead to clinical testing. In addition, with the progression in CT scan and additive manufacturing resolution, more defined features can be designed and produced, and compliance can be achieve at a higher degree.

8. Acknowledgements

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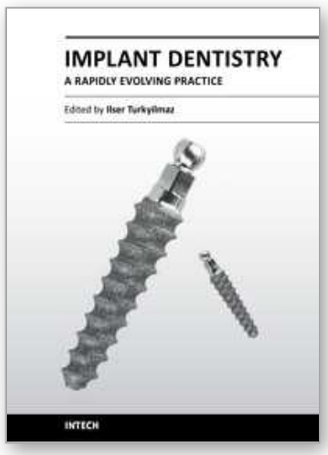
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Implant dentistry has come a long way since Dr. Branemark introduced the osseointegration concept with endosseous implants. The use of dental implants has increased exponentially in the last three decades. As implant treatment became more predictable, the benefits of therapy became evident. The demand for dental implants has fueled a rapid expansion of the market. Presently, general dentists and a variety of specialists offer implants as a solution to partial and complete edentulism. Implant dentistry continues to evolve and expand with the development of new surgical and prosthodontic techniques. The aim of Implant Dentistry - A Rapidly Evolving Practice, is to provide a comtemporary clinic resource for dentists who want to replace missing teeth with dental implants. It is a text that relates one chapter to every other chapter and integrates common threads among science, clinical experience and future concepts. This book consists of 23 chapters divided into five sections. We believe that, Implant Dentistry: A Rapidly Evolving Practice, will be a valuable source for dental students, post-graduate residents, general dentists and specialists who want to know more about dental implants.

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