Oral Implants: The Paradigm Shift in Restorative Dentistry

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N.P. Lang[1]

Abstract

The discovery of the phenomenon "osseointegration," or functional ankylosis, has led to the development of oral implants with high clinical performance. Consequently, the placement of titanium implants has changed the paradigms of restorative dentistry. Implants are used to prevent placing reconstructions anchored on natural teeth when these are vital and intact. Furthermore, implants are suitable to improve subjective chewing function and to replace missing and strategically important abutments. The osseointegration process is characterized by a predictable sequence of healing events that encompass the formation of woven bone, parallel fibers, and lamellar bone and result in fully functional bone that will remodel throughout life. While the osseointegration facilitates the use of implants as prosthetic abutments, it has to be kept in mind that the peri-implant soft tissue may be subject to biological complications. This, in turn, may result in an infectious process that will jeopardize the osseointegration. Consequently, the monitoring of the peri-implant tissues is an important aspect, and early intervention in situations with peri-implant mucositis is mandatory for the prevention of peri-implantitis. Hence, it is evident that oral implants need lifelong maintenance care if their longevity is to be assured.

Keywords: periodontics, wound healing, osseointegration, implant stability, clinical indications, history

Historic Development

In the first half of the 20th century, dentists started to place subperiosteal frameworks to provide fixation prongs for better denture stability in fully edentulous patients. Owing to the neglect of microbiological aspects and the risks for infection associated with these operations, most of such "implants" were lost in a relatively short time, and the loss was associated with major infection and extensive loss of alveolar bone in regions with an already minimal bone volume. Obviously, subperiosteal implants never gained popularity.

A second generation of oral implants was gaining attention in the 1960s. They healed by fibrous encapsulation. These blade implants were predominantly manufactured from stainless steel (Linkow 1970) and consequently were perceived as a foreign body. Moreover, the preparation of the implant bed was not precisely congruent with the blade and allowed micromovements during healing. Again, the connection through the mucosal tissue into the oral environment provided a port of entry for bacteria. As a consequence, blade implants were susceptible to infections and were often lost as a result of advanced bone loss.

It was not until it was realized that only materials of high resistance to corrosion were suitable for tissue integration. Titanium and titanium alloys were recognized as such metals. Now, another generation of implants resulted in a new phenomenon in healing. Bone cells would grow directly onto titanium and completely integrate the foreign body into bone tissue.

This phenomenon was first discovered by P.-I. Brånemark (Brånemark et al. 1969) when wound chambers made out of titanium were impossible to retrieve from experimental animals after completion of the experiment. The process was defined as direct bone-to-implant contact on a microscopic level and termed "osseointegration." This clearly represents the third generation of oral implants. In 1977, Brånemark and his coworkers (1977) reported the first study with successfully integrated titanium implants after 10 y in function.

During the same decade, the Association for the Study of Internal Fixation (AO Foundation; orthopedic surgeons) developed fixation devices for osteosynthesis and discovered that screws made out of titanium would osseointegrate and remain stable. This phenomenon, like osseointegration, was termed "functional ankylosis" by A. Schroeder (Schroeder et al. 1976; Schroeder et al. 1981). It was demonstrated that only metals of a high resistance to corrosion, such as titanium or zirconium, would have the property of osseointegrating and to heal by direct bone-to-implant contact (Steinemann 1998). Consequently, this principle found its way into implant dentistry.

A third immediate implant system (Schulte et al. 1978) made out of aluminum oxide was propagated by a clinical research group in Tübingen, Germany. Close to 100 implants were documented up to 2.5 y. However, this system did not result in stable and satisfactory outcomes and was abandoned later.

[1]Department of Periodontology, School of Dental Medicine, University of Berne, Berne, Switzerland

Corresponding Author:
N.P. Lang, Department of Periodontology, School of Dental Medicine, University of Berne, Freiburgstrasse 7, CH- 3010 Berne, Switzerland.
Email: nplang@switzerland.net

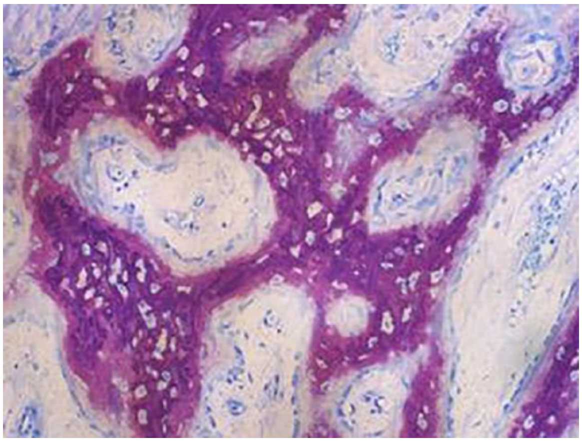

Figure 1. Woven bone surrounding a titanium oral implant. First stage of gap healing between the implant surface and the pristine bony walls of the implant bed after homeostasis and formation of a coagulum. Trabecular structures develop adjacent to the vasculature within the first week and connect the parent bone to the implant surface. Undecalcified ground section surface stained with toluidine blue and basic fuchsin. *Courtesy of Prof. Dr. D.D. Bosshardt, University of Berne.*

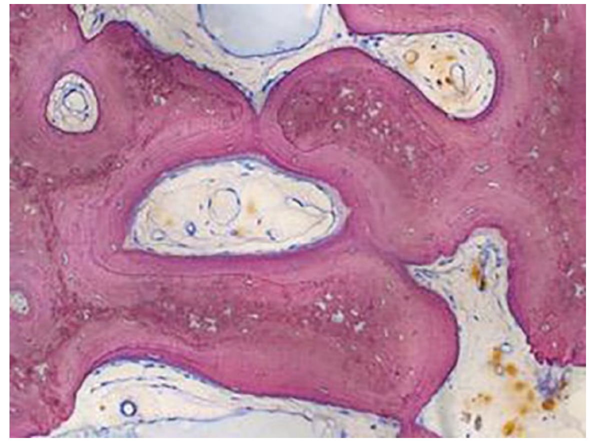

Figure 2. After reaching some thickness of the woven bone trabeculae, parallel-fibered bone—followed by the deposition of lamellar bone—increases the bony density until primary osteons are formed. Undecalcified ground section surface stained with toluidine blue and basic fuchsin. *Courtesy of Prof. Dr. D.D. Bosshardt, University of Berne.*

Osseointegration or Functional Ankylosis

In the gap between the pristine bone of an implant bed and the implant body, a perfect healing is observed with a true regeneration of the bony tissue fully restoring the original structure and function (Johansson and Albrektsson 1987; Schenk and Buser 1998). Sequential studies on the events of this healing revealed that the osseointegration process always followed the same stages in bone formation (Abrahamsson et al. 2004). At the initiation of the process, bone matrix is exposed to extracellular fluids, noncollagenous proteins, and growth factors. These are set free and activate bone repair. Attracted by chemotaxis, osteoprogenitor cells of the bone marrow migrate into the site of the gap. They proliferate and differentiate into osteoblast precursors and osteoblasts. They start bone deposition from the pristine gap walls (distant osteogenesis) and, depending on the surface configuration of the implant, the implant surface itself (contact osteogenesis).

The activated osseointegration process follows a preset biologically determined program that is recognized in 3 stages (Bosshadt et al. 2017):

Stage 1: Incorporation by woven bone formation
Stage 2: Adaptation of bone mass to load and function (lamellar and parallel-fibered bone deposition)
Stage 3: Adaptation of bone structure to load (bone modeling and remodeling)

Woven Bone Formation

This first deposited bone tissue is often considered a primitive or immature bone characterized by a random felt-like orientation of its collagen fibrils. Numerous irregularly shaped osteocytes are observed. But this bone has an outstanding capacity of forming a scaffold of trabeculae and hence is able to spread into the surrounding tissues at a relatively rapid rate. The formation of the primary scaffold is coupled with the formation of the vascular network and results in the development of the primary spongiosa that is able to bridge gaps <1 mm within only a couple of days. Woven bone is the ideal filler to open spaces and for the construction of bony bridges between the walls of an implant bed and the implant surface (Fig. 1).

Woven bone formation dominates the first 4 to 6 wk after implant surgery.

Deposition of Parallel-Fibered and Lamellar Bone

The second act in the scenario of bone formation starting in the second month after surgery is the reinforcement of the primary spongiosa. Microscopically, the structure of bone deposition changes either to well-recognized lamellar bone or toward a parallel-fibered bone. Lamellar bone is the most elaborate type of bone tissue. Comparable to plywood, packing of collagen fibrils into parallel layers with an alternating course results in the highest ultimate strength. Parallel-fibered bone is an intermediate stage between woven and lamellar bone. The collagen fibrils run parallel to the surface but without preference in orientation in that plane (Fig. 2).

The linear apposition rate of human lamellar bone is only 1 to 1.5 µm/d. For parallel-fibered bone, it is 3 to 5 times larger (Schenk and Buser 1998). Both bone types cannot form scaffolds like woven bone. They merely grow by apposition.

Bone Modeling and Remodeling

Bone modeling is the last stage in maturation of bone. It starts around 12 wk after surgery and is seen predominantly after several weeks of high activity. Then, it may slow down again. But bone remodeling continues throughout life (Schenk and Buser 1998). In cortical and cancellous bone, bone remodeling occurs in discrete units that are called "bone multicellular

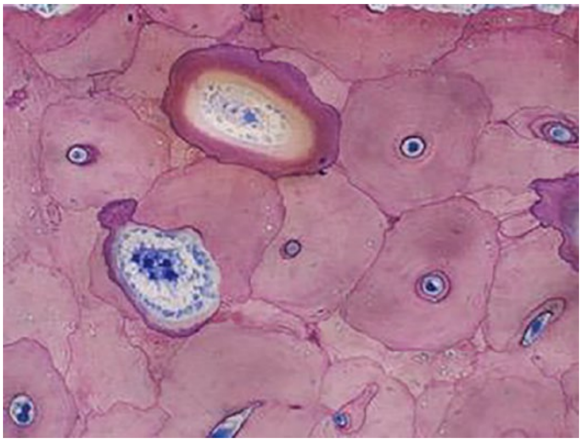

Figure 3. At approximately 8 wk of healing, bone growth and reinforcement result in a further increase in bone density. Remodeling replacing primary bone with secondary osteons starts. Secondary osteons with osteoclastic activity and seams of osteoblasts leading to bone apposition in a lamellar way are visible around the central blood vessels of the osteon. Undecalcified ground section surface stained with toluidine blue and basic fuchsin. *Courtesy of Prof. Dr. D.D. Bosshardt, University of Berne.*

units" (BMUs). Remodeling starts with osteoclastic resorption and is followed by lamellar bone deposition. Resorption and bone formation are spacially and timely coupled. In cortical bone, a BMU consists of a squad of osteoclasts that acts like a cutting cone. They form a kind of drill head and produce a cylindrical resorption canal with diameters equal to those of an osteon (i.e., 150 to 200 µm). This cutting cone advances at a speed of about 50 µm/d. It is followed by a vascular loop accompanied by perivascular osteoprogenitor cells. Approximately 100 µm behind the osteoclastic squad, the first osteoblasts line up onto the wall of the resorption canal. These cells begin to deposit concentric layers of lamellar bone. The completion of a new osteon takes about 2 to 4 mo (Fig. 3). In cancellous bone, the concept of the BMU is also valid. On the trabecular surface, remodeling starts with an accumulation of osteoclasts to produce an erosion bay. Osteoblasts appear and refill the eroded space with new lamellar bone a few days later.

In more recent times, industry provided implant surfaces that were nanotechnologically modified to speed up the osseointegration process (Lang et al. 2011). As of now, it may be claimed that oral implants made out of titanium or zirconia with appropriate implant surface configurations and surface chemistry have a predictable healing pattern (Bosshardt et al. 2017). This results in a high degree of confidence for implant therapy. It is documented that close to 99% of such implants do osseointegrate and represent reliable and stable prosthetic abutments in reconstructive dentistry. Although the osseointegration is perceived as a predictable phenomenon, it has to be noted that oral implants are susceptible to peri-implant infection, leading to marginal bone loss and eventually implant loss.

Hence, it is important to realize that tissue integration addresses not only osseointegration but also the integration into the soft peri-implant tissues and the establishment of a peri-implant seal with an epithelial attachment and a zone of supracrestal fiber adaptation (Fig. 4).

Figure 4. Overview of an osseointegrated titanium implant with an SLA surface. Almost perfect coating of the implant surface with bone. Moreover, the transmucosal soft tissue seal is clearly visible. The epithelial attachment extends approximately 2 mm around the neck of the implant. Apically to the junctional epithelium is a region of connective tissue adaptation with fibers running parallel to the direction of the implant neck. This soft tissue cuff represents a seal that has been termed "biologic width." It is slightly wider than the corresponding supracrestal fiber region at teeth. Undecalcified ground section surface stained with toluidine blue and basic fuchsin. *Courtesy of Prof. Dr. D.D. Bosshardt, University of Berne.*

Interface between the Mucosa and the Implant

In the 1990s and the first decade in this century, the interface between the soft tissues and the implant surface has been a subject of extensive study, predominantly by periodontal researchers (Berglundh et al. 1991). In a Beagle dog model, the structural characteristics of the peri-implant mucosa were compared with those of the gingiva adjacent to 3 well-established implant systems. The healthy soft tissues adjacent to implants or teeth have a firm consistency and display several microscopic features in common but also significant differences. Both the gingiva and the keratinized peri-implant mucosa are lined by a keratinized oral epithelium that is continuous with a junctional epithelium. The latter is approximately 2 mm long. At the tooth site, it terminates at the cementoenamel junction, apical of which an acellular extrinsic fiber cementum establishes a significant component of the supra-alveolar attachment apparatus (Berglundh et al. 1991).

At the site of the implant, the apical portion of the junctional epithelium is consistently separated from the alveolar bone by a zone of noninflamed collagen-rich but cell-poor connective tissue. This region is about 1 to 1.5 mm high and is continuous with the junctional epithelium. With the epithelium, an implant-mucosa attachment of approximately 3 to 4 mm in height is established. In the collagen-rich region, the fibers invest in marginal bone and run a course more or less parallel to the implant surface.

A consistent finding in many studies was the observation that the junctional epithelium never reached the alveolar crest, even after prosthetic abutment connection, but consistently terminated about 1 mm coronal to the alveolar crest. This indicated that the proliferation of the junctional epithelium during wound healing of the mucosal flap was stopped by contact inhibition—that is, an interaction of the titanium dioxide surface and the coronal part of the supracrestal connective tissue. The dense connective tissue in the peri-implant soft tissue facilitated the seal mediated by the junctional epithelium.

Both in the Beagle dog model and in human biopsies, the sequential events of soft tissue healing have been studied (Berglundh et al. 2007; Lang et al. 2011). It was observed that the soft tissue seal assumed its composition and outline after approximately 4 to 6 wk following implant installation. While the fractional content of the connective tissue in the peri-implant region remained relatively stable after this time, major changes in tissue components occurred before 4 wk. Hence, it has to be realized that the peri-implant soft tissue seal is established with clinically stable proportions of tissue components first after 4 wk of healing.

Biological Complications at Implant Sites

As titanium or zirconia surfaces represent hard nonshedding surfaces in a fluid system, they are subject to biofilm deposition (Mombelli et al. 1988). Primary plaque-forming microorganisms, predominantly gram-positive cocci and/or rods, colonize the surface following the deposition of a protein pellicle on the implant surface. With time, the single organisms proliferate into colonies and occupy the entire exposed surface of the implant. With time, the colonization of the biofilm becomes more complex, including microorganisms of higher pathogenic potential. Consequently, the biofilm will trigger a host response in the form of inflammation that starts locally subjacent to the soft tissue seal, called "mucositis." This stage of a peri-implant disease is reversible (Salvi et al. 2012) and represents a precursor stage to the more advanced lesion termed "peri-implantitis." The latter is characterized by inflammation, an increase in peri-implant probing depth, and bone loss (Mombelli and Lang 1992; Serino et al. 2013). Once peri-implantitis is established, the lesions may progress much faster than identified for the attachment loss around teeth. Many of the peri-implantitis-affected implants will be lost through advanced bone loss. Epidemiologically, it is assumed that the incidence of peri-implantitis after 10 y of function is as high as 10% of the implants in 20% of the patients (Mombelli et al. 2012). Hence, peri-implantitis represents a true health problem for the implant patient.

Possible Prevention of Peri-implantitis

Owing to the infective nature of peri-implantitis, the incidence of this disease may be substantially reduced by systematically applying an antibiofilm strategy starting with the recruitment of the implant patient and all the way through monitoring and maintenance care following therapy. In essence, this means the following:

- The implant patient has to perform daily oral hygiene practices at a high standard (Salvi and Ramseier 2015; Serino et al. 2015).
- Implants should first be installed in dentitions that are free from oral infections, such as periodontal disease. Following active periodontal therapy, no residual pockets (>5 mm) should be present, as they represent reservoirs of pathogens from which colonization of the implants with pathogens may originate (Mombelli et al. 1995).
- Implant patients should be offered a well-organized regular recall system for professional maintenance care. Monitoring of implants for bleeding on probing, suppuration, and increased probing depth is mandatory (Roccuzzo et al. 2018).
- Early signs of peri-implant mucositis should be recognized, and mucositis is to be treated to prevent peri-implantitis (Costa et al. 2012).
- Prostheses have to be designed to allow meticulous biofilm removal. They must not jeopardize the patients' efforts to perform optimal oral hygiene (Serino and Ström 2008).
- Implant placement has to be compatible with the possibility to cleanse the prosthetic appliances. Too many implants may be detrimental to this concept (Daudt Polido et al. 2018).
- Moreover, in addition to cleansability, the design of the prostheses and the prosthetic marginal fit have to be perfect. Excess cement must be diligently removed (Linkevicius et al. 2013).
- It has to be realized that patients susceptible to periodontitis may also be more susceptible to the development of peri-implantitis (Karoussis et al. 2004).

Changing Paradigms in Restorative Dentistry

Originally, oral implants were used to provide better stability for complete dentures in edentulous patients. As implant installation became more predictable and the longevity of oral implants was documented to approach 90% to 95% after 5 y, implants were propagated to also *replace missing teeth* in partially edentulous patients. Today, these indications are predominant in the reconstruction of mutilated dentitions. In essence, 3 indications may be defined (Lang and Salvi 2015):

Tooth replacement with preservation of tooth substance of adjacent teeth: This means that single-tooth replacement is most likely to be preferred by single-tooth implant placement instead of a 3-unit fixed dental prosthesis. This represents the most biological way of tooth replacement. Figure 5 demonstrates that the replacement of a missing front tooth is best accomplished by placing a single implant either shortly after tooth loss or later (i.e., delayed) when soft tissue healing is complete. Like that, the integrity of the adjacent teeth may be retained.

Increasing subjective chewing comfort: In completely edentulous patients, chewing comfort may substantially be improved by placing 1 or 2 locator implants for overdenture retention. Today, this simple treatment has been accepted by the prosthodontic community as the standard of care for the edentulous patient. Figure 6 illustrates a typical situation in which denture retention is substantially improved by the placement of only 2 locator abutments. Moreover, increasing subjective chewing comfort by adding single–premolar equivalent chewing units in, for example, free-end situations represents a frequently applied indication and replaces the need for the incorporation of a removable partial dental prosthesis. This may be achieved with the placement of 1 or 2 single implants placed at a distance from the most distal abutment in the dentition with dimensions that follow the concept of providing accessibility for optimal individual cleansing (Fig. 7).

Replacing strategically important missing teeth: Various strategic implant placements may facilitate the successful reconstruction of a partially edentulous patient. Such implants may be used to construct a dental arch in the case of missing anterior teeth.

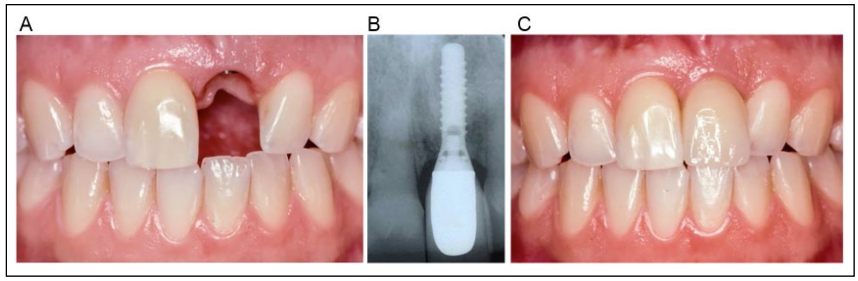

Figure 5. Missing tooth 21 four weeks after extraction. (**A**) Clinical situation of an extraction socket in healing. (**B**) Replacement of the missing tooth with a single tissue-level implant. Radiographic image after 2 y following prosthetic reconstruction. Bone level with minimal resorption (<1 mm). (**C**) Clinical situation after 5 y. Functionally and aesthetically satisfactory outcome with healthy peri-implant mucosa. Single-tooth replacement to preserve the adjacent teeth representing the most biological reconstruction of the missing 21. *Courtesy of Prof. Dr. G.E. Salvi, University of Berne.*

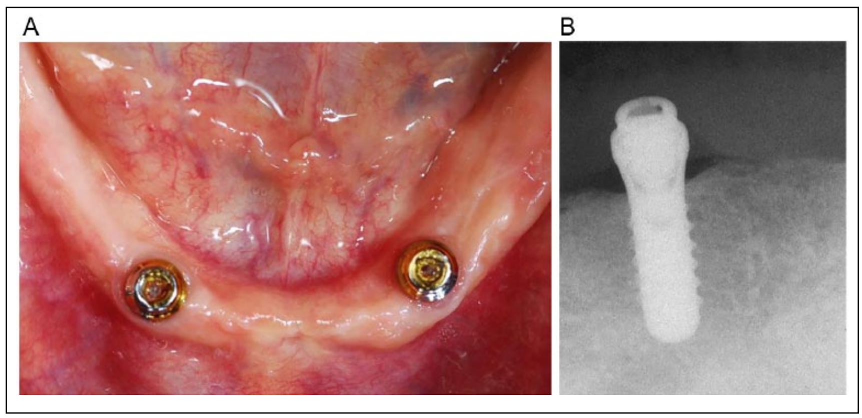

Figure 6. Edentulous mandible. (**A**) Increasing the chewing comfort and improving the stability of a complete over denture with 2 locator implants. Standard of care for today's reconstruction in edentulous patients. (**B**) Well-maintained locator abutment after 5 y of function. Minimal bone remodeling and minimal bone resorption (<1 mm). *Courtesy of Prof. Dr. G.E. Salvi, University of Berne.*

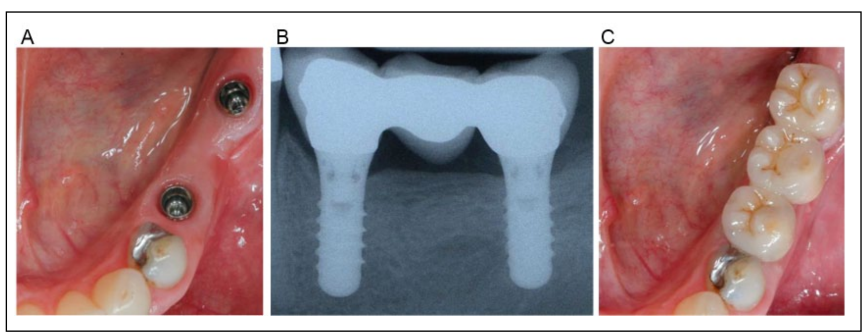

Figure 7. Increasing subjective chewing comfort in a partially edentulous patient. (**A**) Clinical situation after implant placement in a free-end situation. Implants were placed at a distance of 5 mm from the distal surface of tooth 34 (replacement of tooth 35) and at a distance of 19 mm (replacement of tooth 36/37) to incorporate a 3-unit bridge. (**B**) Radiographic evaluation after 5 y. Minimal bone resorption (<1 mm). (**C**) Five years after incorporation of an implant-supported 3-unit fixed dental prosthesis. *Courtesy of Prof. Dr. G.E. Salvi, University of Berne.*

Preservation of Natural Tooth Substance

To preserve natural tooth substance or existing satisfactory reconstructions that do not need replacement, oral implants serve as ideal abutments. In this respect, the preparation of a tooth that would result in the accidental opening of 40,000 to 70,000 dentinal tubules/mm^2 may be avoided. Hence, the integrity of a tooth would be preserved. It has been documented that approximately 10% of prepared vital abutment teeth will lose their vitality in the course of 10 y (Bergenholtz and Nyman 1984; Pjetursson et al. 2004). Obviously, the avoidance of tooth preparations represents the most biological way for replacing a missing tooth (Fig. 5). Even in an area of aesthetic priority, the replacement of a missing tooth may result in the most aesthetic treatment option if an adequate bone volume is available. This is especially true for a periodontally healthy dentition with a clinical situation in which the papillae of the teeth adjacent to the edentulous area are still present.

Moreover, clinicians may choose to save existing but still satisfactory reconstructions in their efforts to replace missing teeth, thereby simplifying the restoration. The reconstruction may be reduced in extent; hence, the chance for encountering technical complications may be reduced as well during future years of service.

Increasing Subjective Chewing Comfort

It has been demonstrated that the installation of only a few oral implants may dramatically improve the chewing function in edentulous patients (Lundqvist and Haraldson 1992), especially if the alveolar process is severely atrophied (Fontijn-Tekamp et al. 2000). The completely edentulous patient may benefit from as few as 2 oral implants placed in the mandibular canine region (Fig. 6).

Moreover, subjective chewing capacity may be improved in partially edentulous dentitions with missing teeth in the premolar region by supplementing single chewing units or implant-supported 3-unit fixed dental prostheses to extend a shortened dental arch and satisfy the patient's chewing capacity (Fig. 7). It is imperative that the implants be placed in the prosthetically correct location, leaving adequate space for the application of interimplant cleansing devices. Depending on the nature of the prosthetic crown of a premolar unit (7 mm) or a molar unit (8 mm) to be replaced, the interimplant space has to be properly designed.

Replacement of Strategically Important Missing Teeth

The loss of strategically important teeth often results in a chain reaction of therapeutic measures that complicate the reconstruction of a mutilated dentition.

Especially in dentitions that had received multiple reconstructions, the loss of 1 strategic abutment may lead to time-consuming and costly therapy. Oral implants may substantially simplify the treatment and allow the reconstruction of the dentition with smaller and less risky reconstructions than if traditional fixed prosthodontics should be chosen. By placing oral implants in the strategically correct location, partial reconstruction of a dentition may become possible. It is clear that such implants have to be restoratively driven. However, in cases with inadequate bone volume in the respective sites, bone augmentation procedures have to be performed and hence may render the prosthetic treatment more complex.

Dental Implants as a Panacea?

The euphoric perspectives of implant dentistry have led practitioners to believe that oral implants have a better prognosis than, for example, a compromised tooth; hence, tooth extraction is often recommended to patients instead of tooth retention and proper traditional dental therapy. The clearly visible trend affecting clinical practice over the past 2 decades, with a reduced emphasis to "save compromised teeth," has brought a treatment philosophy that is completely uncritical over the installation of oral implants. Despite a predictable prognosis for osseointegrated implants, the truth is that biological complications, such as peri-implant mucositis and peri-implantitis, are common for implant therapy (Derks et al. 2016). This fact is highly underestimated. However, excellent long-term results of successful therapy for tooth preservation therapies have been presented (Axelsson et al. 2004; Lindhe and Pacey 2014)

In the light of these facts, it would appear to be logical to advocate that treatment philosophies should change to retain more teeth. If early removal of compromised teeth and subsequent installation of implants remains the preferred paradigm, the dental profession may lose most of its expertise to preserve a functional dentition for the patient's life (Giannobile and Lang 2016).

Author Contributions

N.P. Lang, contributed to conception, design, and data acquisition, drafted and critically revised the manuscript. The author gave final approval and agrees to be accountable for all aspects of the work.

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