Clin Oral Impl Res 2000: 11 (Suppl.): 33–58
Printed in Denmark · All rights reserved

CLINICAL ORAL
IMPLANTS RESEARCH
ISSN 0905-7161

Chapter 2

The scientific basis for and clinical experiences with Straumann implants including the ITI® Dental Implant System: a consensus report

Cochran DL. The scientific basis for and clinical experiences with Straumann implants including the ITI® Dental Implant System: a consensus report.
Clin Oral Impl Res 2000: 11 (Suppl.): 33–58. © Munksgaard 2000.

Successful endosseous implant therapy requires integration of the implant with bone, soft connective tissue and epithelium. This report from a consensus conference on Straumann dental implants including the ITI® Dental Implant System documents the interaction of these nonsubmerged one-piece implants with the oral tissues and reviews clinical studies supporting the high success achievable with these implants in patients. Light and electron microscopy reveal that epithelial structures similar to teeth are found around the implants. A connective tissue zone exists between the apical extension of the junctional epithelium and the alveolar bone. This connective tissue comprises a dense circular avascular zone of connective tissue fibers surrounded by a loose vascular connective tissue. The histologic dimensions of the epithelium and connective tissue comprising the biologic width are similar to the same tissues around teeth. The nonsubmerged one-piece design of the Straumann implants, which have been used for over 20 years, has set a standard in implant dentistry, with other implants now being manufactured and placed using similar techniques. Straumann implants have an endosseous portion that is either coated with a well-characterized and well-documented titanium plasma-sprayed surface or is sandblasted and acid attacked. Both surfaces have been shown to have advantages for osseous integration compared to machined and other smoother implant surfaces. These advantages include greater amounts of bone-to-implant contact, more rapid integration with bone tissue, and higher removal torque values. The lack of component connection at or below the alveolar crest provides additional benefits. Component connection at the alveolar crest, as seen with submerged implants, results in microbial contamination, crestal bone loss and a more apical epithelial location. Numerous human clinical trials document the successful use of Straumann implants in a variety of indications and areas of the mouth. These include prospective long-term trials using strict criteria of success and life table analyses. Taken together, the clinical studies reveal that Straumann implants can be used predictably in partially edentulous and completely edentulous maxilla and mandibles with high success rates. Furthermore, the animal and microscopic studies reviewed provide a scientific basis for the integration of Straumann implants with bone, connective tissue and epithelium.

David L. Cochran

Department of Periodontics, The University of Texas Health Science Center at San Antonio, USA

Key words: dental implants – osseointegration – soft tissue integration – one-stage implants – nonsubmerged implants – clinical implant trials – consensus conference

Committee Members:
Prof. Pedro Bullon Fernandez, Dr. Joseph P. Fiorellini, Dr. med. dent. Christoph H. Hämmerle, Dr. Joachim S. Hermann, Prof. Erik Hjørting-Hansen, Prof. Dr. Robert K. Schenk, Dr. James P. Simpson, Prof. Dr. Samuel Steinemann, Prof. Giorgio Vogel, Dr. Hans-Peter Weber

Prof. David L. Cochran, Chairman, Dept. of Periodontics, The University of Texas Health Science Center at San Antonio, 7703 Floyd Curl Drive, San Antonio, TX 78284–7894, USA
Tel.: +1 210 567 3600
Fax: +1 210 567 6299
e-mail: cochran@uthscsa.edu

The intent of this review was to examine the biological and clinical considerations of implant therapy utilizing the ITI® Dental Implant System and former dental implants produced by the Institute Straumann. Different types of implants have been used clinically as refinements have been made in the design of the implant over the years, and for the purpose of this review, all dental implants produced by Institute Straumann will be referred to as Straumann implants. In those cases where a specific product is referred to, that type of implant will be designated. Although specific design issues have been changed over the years, several critical aspects of the implants have remained the same, including the one-part nonsubmerged design, a roughened surface for osseous integration on a commercially pure titanium implant of grade IV that has been strengthened by a proprietary process, and a relatively smooth machined surface on the coronal aspect of the implant for soft tissue integration. A critical review of the literature was conducted, oriented toward determining clinical efficacy and validity of available supportive information. Full-length articles published in English in peer-reviewed journals or peer-reviewed symposia proceedings were emphasized.

This review specifically covered the scientific basis for Straumann implant integration including soft and hard tissues. In addition, the clinical performance of various Straumann products was reviewed. Most tissue culture or finite element studies were not included, as a comprehensive evaluation of this literature would not add significantly to the clinical practice of the ITI dental implant at present. This review represents one part of a consensus conference conducted in Lucerne, Switzerland, in August 1997 by the International Team of Oral Implantology (ITI), a group of clinicians, scientists and individuals dedicated to the advancement of the field of oral implantology.

Implant soft tissue integration

Overview

The predominant biological considerations in endosseous implant dentistry have focused on the bone-to-implant interface, since predictable implant anchorage requires the implant to directly contact the bone tissue (Cochran 1996). Schroeder et al. (1976, 1978, 1981), using Straumann dental implants, described a nonsubmerged technique of endosseous implant placement in which the implant extended above the bone and the soft tissues were in direct contact with the implant at the time it was initially placed. The difference in the placement of submerged and nonsubmerged implants has been described, as well as the consequences of the nonsubmerged technique (Cochran & Mahn 1992).

Transgingival structures in the oral cavity, such as teeth and implants, must penetrate the soft tissues, comprising connective tissue and epithelium. This ensures the integrity of the integument by forming a seal between the inside of the body and the outside environment. The placement of implants using a nonsubmerged approach allows for the formation of a biologic width from the time of implant placement (Cochran & Mahn 1992; Cochran et al. 1997; Weber et al. 1996). This includes the formation of sulcus depth, epithelial attachment, and connective tissue contact to the implant surface. Thus, the implantogingival tissues serve a similar barrier function as dentogingival tissues, and the integration of the implant necessitates the integration of all three types of tissues: bone, soft connective tissue, and epithelium. When the implantogingival tissues are seen as a barrier, it is important to consider two aspects of the soft tissues surrounding implants: the morphology (structure) and the physiological function of the implantogingival junction.

Direct contact of the implant with soft tissues

An early study in monkeys described the soft tissue contact with various implant surfaces around 30 nonsubmerged implants (Schroeder et al. 1981). Implants placed in attached keratinized mucosa with minimal inflammation had connective tissue located between the bone and epithelium. The connective tissue contained many fibers with few inflammatory cells. Collagen fibers were in intimate contact with the implant and ran between the implant and the surrounding tissues at the light microscope level. Evidence was described for a "...true adhesion of the epithelium to the implant...," i.e. no space or gap was seen between the epithelium and the implant. Scanning electron microscope (SEM) and transmission electron microscope (TEM) analyses indicated that the connective tissue contact with the titanium plasma-sprayed surfaced implant was composed of a fibrous layer of interwoven fiber bundles firmly adherent to the surface of the implant. At this level, and against the rough surface, the fibers appeared to be functionally (more perpendicularly) oriented. SEMs also revealed epithelium with intercellular junctions and desmosomes. Hemidesmosomes were not observed in the sections of the rough surface, but the investigator acknowledged the technical difficulties in visualizing the titanium plasma-sprayed-epithelium interface. A basal lamina was observed between the epithelium and the titanium plasma-sprayed particles, with microvilli from the

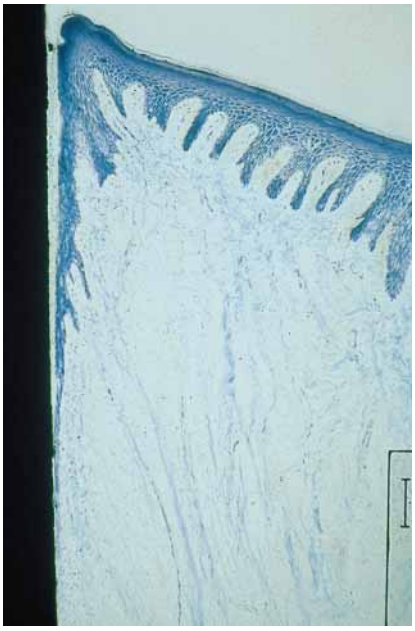

Fig. 2.1. The buccal aspect demonstrates the formation of a peri-implant sulcus lined with a sulcular epithelium (toluidine blue; original magnification ×25). From Buser et al. (1992), Journal of Periodontology, 63: 226–236.

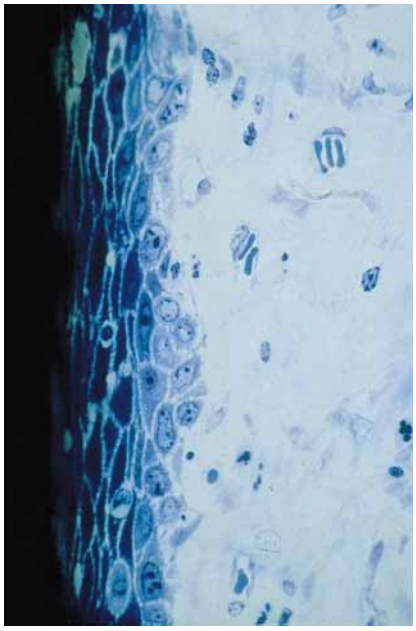

Fig. 2.2. This magnification demonstrates basal and suprabasal cells, and wide intercellular spaces of the junctional epithelium (toluidine blue; original magnification ×250). From Buser et al. (1992), Journal of Periodontology, 63: 226–236.

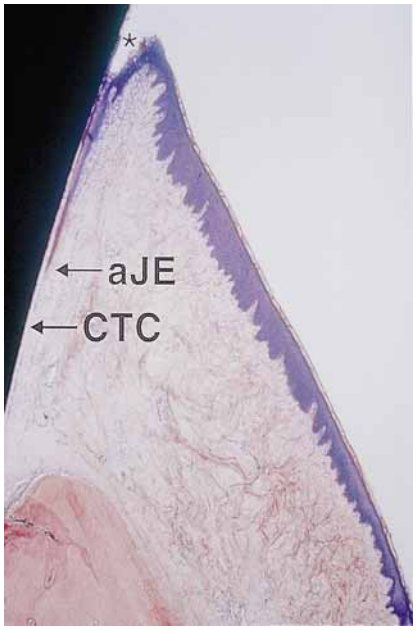

Fig. 2.3. Bucco-lingual section showing the gingiva and the most coronal part of alveolar bone. * shows soft tissues slightly torn away due to nondecalcified histological processing. aJE notes the most apical point of junctional epithelium. CTC identifies connective tissue contact (basic fuchsin stain; original magnification ×12.5; 1-part SLA implants, 3 months unloaded). From Cochran et al. (1997), Journal of Periodontology, 68: 186–198.

epithelial cells extending into the layers of the basal lamina. A conclusion of this study and several others (Gould et al. 1984; James & Schultz 1974; Jansen et al. 1985) was that the fine ultrastructure of the epithelial cells adjacent to the implant was not significantly different from that of other epithelial cells, suggesting that the cells were not influenced by the titanium.

Using a freeze-fracturing technique, an early study (James & Schultz 1974) showed that the junctional epithelium was attached to the implant surface by a basal lamina and hemidesmosomes, similar to the manner in which epithelium is attached to teeth. These findings were confirmed at the EM level using epoxy resin replicas of extracted teeth in monkeys (Listgarten & Lai 1975; Listgarten 1996). This study also demonstrated intact epithelium at the implant surface. A similar relationship of epithelium to titanium or titanium alloys using evaporated layers of metal over plastic implants has also been shown (Gould et al. 1984). And a similar finding was noted in a dog study which used freeze-fractured specimens from aluminum oxide ceramic implants (McKinney et al. 1985).

A histometric study in six beagle dogs compared the soft tissues around nonsubmerged and submerged unloaded implants using a split-mouth design (Weber et al. 1996). Nineteen cylindrical one-piece nonsubmerged implants 2.55 mm in diameter and 8 mm in length had titanium plasma spray (TPS) on the apical 6 mm for placement in the bone tissue. The coronal 2 mm penetrated the mucosa and had a machined surface. The submerged implants were also coated with TPS and had a 0.5 mm machined coronal collar. After initial healing, the submerged implants were uncovered and a 1.5 mm machined abutment was placed on the implant. The resulting gap in these experimental implants was approximately 10 microns. Mandibular premolar teeth were extracted 3 months prior to implant placement. Abutments were placed on the submerged implants after 3 months and the dogs were sacrificed after an additional one and a half months. Clinically detectable erythema was noted in the soft tissues around the implants placed with the submerged approach. This was not observed around the implants placed with a nonsubmerged technique.

Histological analysis revealed that the epithelial

structures that formed were similar to the epithelium found around teeth (Figs 2.1, 2.2). Comparison of the location of the soft and hard tissues around the nonsubmerged and submerged implants showed no difference in the levels around the implants, indicating that the surgical method did not influence the bone or mucosal level. In the case of the epithelium, however, the apical extension was significantly greater for the submerged implants than for the nonsubmerged implants. Consistent with this finding, the connective tissue contact around the submerged implants was located more apically than the connective tissue contact around the nonsubmerged implants. In all cases of the initially submerged implants, the epithelium was found apical to the interface (microgap) between the implant and abutment. The authors speculated that the reason for this apical location of the epithelium around the submerged implants was microbiological contamination of the interface area, as had been demonstrated in studies of two-stage implants (Persson et al. 1996; Quirynen & Van Steenberghe 1993).

Around the nonsubmerged implants the epithelium was never found to extend to the marginal crest level, confirming the findings in an earlier study (Buser et al. 1992a). The combined epithelium (1.18±0.27 mm) and connective tissue (1.35±0.48 mm) contact was 2.95±0.39 mm which was similar to the 2.62 mm found as the mean attachment level in a prospective human clinical trial involving 100 nonsubmerged implants (Buser et al. 1990a). The connective tissue contact found in this study (1.35±0.48 mm) was also similar to the connective tissue contact (1.07 mm) found around teeth (Gargiulo et al. 1961).

Although junctional epithelium around implants originates from the oral epithelium, and the one found around teeth is derived from reduced enamel epithelium (Schroeder & Listgarten 1971), the structures appear identical (Buser et al. 1992a; McKinney et al. 1985; Schroeder et al. 1981; Schroeder 1969). It has been shown that the structural similarities are accompanied by functional similarities. For example, inflammatory infiltrates were found in the connective tissue adjacent to the junctional epithelium of implants and teeth (Lekholm et al. 1986; Listgarten 1992; Sandberg et al. 1993; Seymour et al. 1989). The presence of tissue-plasminogen activator has been reported at the meeting point between junctional and sulcular epithelium of implants (Schmid et al. 1992). These findings are identical to the expression of this enzyme around teeth (Schmid et al. 1991). Further, additional studies have supported the supposition that the junctional epithelium around dental implants is capable of producing some of the same functional characteristics as junctional epithelium around teeth (Tonetti & Schmid 1994, Tonetti et al. 1993).

The dimensions of the biologic width around nonsubmerged loaded and unloaded implants have been reported in another study (Cochran et al. 1997). This report examined the dimensions of the implantogingival junction in relation to 69 clinically healthy unloaded and loaded nonsubmerged implants. Histometric analysis of undecalcified histologic sections included the evaluation of the sulcus depth (SD), the dimensions of the junctional epithelium (JE), and the connective tissue contact (CTC). The dimensions for the unloaded implants after 3 months of healing were 0.49 mm for SD, 1.16 mm for the JE, and 1.36 mm for CTC. These dimensions after 3 months of loading and 6 months of healing were 0.50 mm for SD, 1.44 mm for JE, and 1.01 mm for CTC. After 12 months of loading (15 months healing), these values were 0.16 mm for SD, 1.88 mm for JE, and 1.05 mm for CTC. The sum of these dimensions was similar for the different time points and similar to the same dimensions around teeth. The authors concluded that the "data suggests that a biologic width exists around unloaded and loaded nonsubmerged one-part titanium implants and that this is a physiologically formed and stable dimension as is found around teeth." Thus, these findings demonstrate that the morphology of the soft tissues around unloaded and loaded nonsubmerged oral implants has a biologic width and is similar to the morphology of another transgingival one-part oral structure, a tooth (Figs 2.3–2.5).

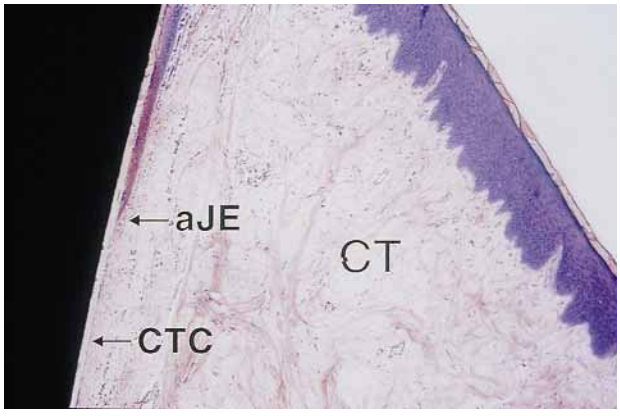

Fig. 2.4. Same aspect as Fig. 2.3 at a higher magnification (basic fuchsin stain; original magnification ×25; 1-part SLA implant, 3 months unloaded). The most apical epithelial cell of the junctional epithelium is indicated (aJE). Note difference between the scar-like connective tissue contact adjacent to the machined titanium surface (CTC) and the connective tissue supporting the oral epithelium (CT and Fig. 2.5). From Cochran et al. (1997), Journal of Periodontology, 68: 186–198.

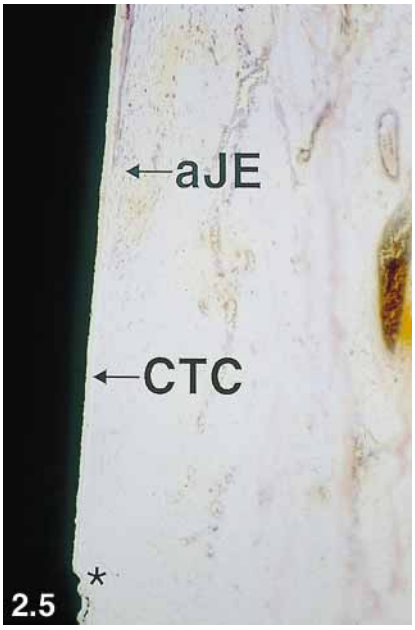

Fig. 2.5. Bucco-lingual section (basic fuchsin stain, original magnification ×50, 1-part SLA implant, 3 months loaded). At the top left, adjacent to the machined titanium surface, the most apical epithelial cell of the junctional epithelium (aJE) is visible surrounded by a few inflammatory cells. At the lower left, the border between the relatively smooth machined and the rough SLA surface is evident (*). Note area of connective tissue contact (CTC) with connective tissue fiber bundles/fibroblasts running parallel to the long axis of the implant between the above-mentioned marked areas. In addition, no blood vessels are apparent in this inner zone, indicating a scar-like connective tissue contact (CTC). From Cochran et al. (1997), Journal of Periodontology, 68: 186–198.

Fig. 2.6. Bucco-lingual section of a rough implant in interference phase contrast. The inner zone demonstrates cross sections of connective tissue fibers (original magnification ×50). From Buser et al. (1992), Journal of Periodontology, 63: 226–236.

The vascular topography of the soft tissues around teeth and implants was compared in two beagle dogs (Berglundh et al. 1994). Around teeth, the vascular supply was derived from supraperiosteal vessels lateral to the alveolar process and from vessels within the periodontal ligament. Implant soft tissue blood supply was derived from terminal branches of larger vessels from the bone periosteum at the implant site. Blood vessels adjacent to junctional epithelium around both teeth and implants revealed a characteristic "crevicular plexus". Furthermore, while peri-implant soft tissues lateral to the implant had sparse blood vessels, soft tissue lateral to root cementum was highly vascularized. The authors concluded that these latter findings confirmed the work of Buser et al. (1992a), in which a connective tissue zone lacking blood vessels was found directly adjacent to the implant surface.

Another paper using immunohistochemistry has confirmed structural differences in healthy human periodontal and peri-implant (ITI Dental Implants) keratinized gingival tissues (Romanos et al. 1995). Collagen types I, III, IV and VII and fibronectin had similar distribution patterns between teeth and implants. Collagen types V and VI had different distributions between teeth and implants. The authors suggested that the greater amount of type V collagen around implants was significant due to its greater collagenase resistance.

Quantitative immunohistochemical methods have been used to compare cell populations in the dentogingival and peri-implant epithelia (Carmichael et al. 1991). Keratin markers numbers 1, 13 and 19 were examined as well as the desmosome markers, desmoplakins I and II. Staining of the desmosomal markers was reduced in the peri-implant mucosa compared to the gingival staining. Additionally, two of the keratins were co-expressed in the peri-implant tissue compared to the gingiva. Otherwise, the staining patterns were similar. The authors concluded that "epithelia of gingiva and peri-implant mucosa are not composed of identical cell populations."

The connective tissue implant interface

In one paper, direct contact of connective tissue with the implant surface in the supracrestal area of nonsubmerged implants in beagle dogs was described (Buser et al. 1992a). It appeared, as was noted above in the study of Schroeder et al. (1981), that the implant surface characteristics influenced the orientation of the collagen fibers. In addition, the orientation of the fibers may have been affected by the relative mobility of the tissues surrounding the implant. The authors of a review paper (Listgarten et al. 1991) reported a difference in orientation between gingival fibers of attached mucosa versus alveolar mucosa. The attached mucosa showed fibers arranged in both parallel and perpendicular directions, while the implants surrounded by alveolar mucosa had only parallel fibers. Rough surfaces demonstrated connective

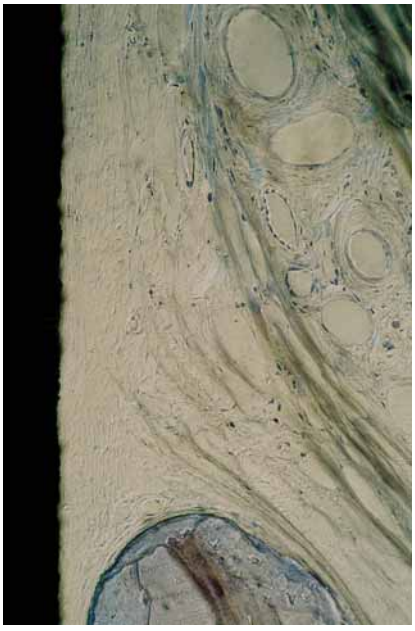

Fig. 2.7. Bucco-lingual section of a rough implant in interference phase contrast. The buccal supracrestal area shows fibers of the gingival connective tissue and the periosteum in the outer zone. Blood vessels are only present in this zone (original magnification ×25). From Buser et al. (1992), Journal of Periodontology, 63: 226–236.

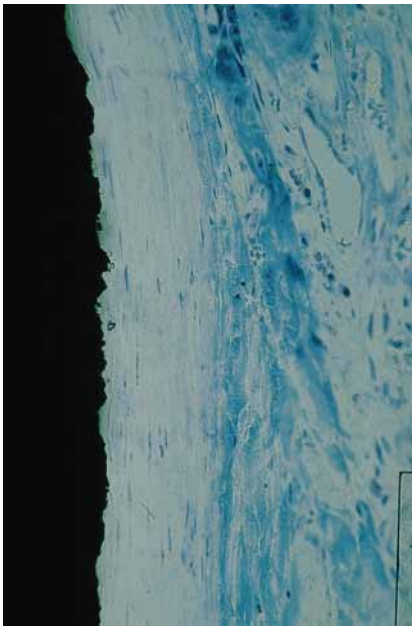

Fig. 2.8. Transverse section of a rough implant. The section demonstrates the circular fiber arrangement and the two different zones of connective tissue. The inner zone is dominated by dense circular fibers, and characterized by the absence of blood vessels. The outer zone reveals thicker collagen fibers and blood vessels (original magnification ×50). From Buser et al. (1992), Journal of Periodontology, 63: 226–236.

Fig. 2.9. Transverse section of a rough implant (polarized light). The mesial aspect demonstrates a ring of dense circular fibers in the inner zone. Diagonally running fibers from the outer zone (arrows) enter the ring of circular fibers in the inner zone (original magnification ×20). From Buser et al. (1992), Journal of Periodontology, 63: 226–236.

tissue attachments with better-developed, perpendicularly-oriented dense fibers compared to the smoother surfaces.

In the study by Buser et al. (1992a), soft tissue healing was evaluated around 24 nonsubmerged implants with different surface characteristics, ranging from very smooth to rough. This study examined transmucosal implants in beagle dogs using light microscopy three months after placement. A peri-implant sulcus was demonstrated which consisted of a non-keratinized sulcular epithelium and a junctional epithelium. No epithelial proliferation to the alveolar crest was found. A direct connective tissue contact was observed that was 50–100 μm wide and contained dense circular fibers without blood vessels. Outside this area, connective tissue was less dense, with horizontal and vertical collagen fibers and numerous blood vessels (Figs 2.6–2.9). No differences were found in the connective tissues between the rough sandblasted, fine sandblasted, and polished surfaces. There was, however, a significantly higher level of bone found for the rougher surfaces compared to the smoother surfaces.

Titanium-coated epoxy resin replicas of smooth and plasma-sprayed implants have been used to examine tissue reactions at a light microscopic and ultrastructural level (Listgarten 1992). No perpendicular fibers were found contacting the implant surface. Fibers were found to be running apicocoronally, circumferentially, and in other directions parallel to the implant surface. While there was no evidence of fiber insertion into the titanium coating, the moderately dense network of collagen fibrils surrounding the implant did come into direct contact with the coating. These fibers seemed to splice with circumferentially oriented fibers more distant from the implant.

These findings were confirmed in two studies that demonstrated a "circular ligament" of densely packed collagen fibers free of inflammatory cells and running parallel around nonsubmerged titanium screws in the maxillary bone of monkeys (Ruggeri et al. 1992, 1994). The characteristics of the implant surface used in these studies were not given in these articles. The authors concluded, however, that keeping the implant nonsubmerged did not influence its survival, and that the smooth neck of the implant was surrounded by a narrow sulcus with junctional-like epithelium and few in-

flammatory cells (Ruggeri et al. 1994). The collagen fibers originated from the bone crest, adjacent teeth, and epithelial papillae, and converged on the implant to form the circular fibers around the implant. Histochemical analysis revealed the presence of highly sulfated proteoglycans around the connective tissue fibrils. From this and previous studies, these investigators also suggested that rougher implant surfaces (using titanium plasma-sprayed implants) resulted in a more perpendicular alignment of the fibers than did the smoother surfaces, which resulted in a parallel arrangement. However, there was no evidence for a direct attachment of those fibers.

Types of epithelium

One question discussed repeatedly with regard to the soft tissues around implants has been whether the presence of keratinized mucosa is required for implant success (Krekeler et al. 1985). Meffert et al. (1992) provided an excellent review of the literature available on this topic prior to the early 1990s. Several more recent papers have also addressed this issue. One study described the placement of 69 ITI implants in 33 elderly patients and followed them for five years (Mericske-Stern et al. 1994). Each patient received two implants in the mandible to support overdentures. Approximately half of the implants were in mucosa and therefore had no keratinized tissue around the implant. This tissue was maintained in a healthy condition over the five years with minimal or no attachment loss and with an average pocket depth of approximately 3 mm. There was a tendency (which was statistically significant for certain areas) for the width of the keratinized mucosa to increase over time. Interestingly, these authors divided their patients into those who had been edentulous for a shorter period (implants placed within two years after the last tooth was lost) versus those who had been edentulous for longer periods (at least five years since last tooth loss). Patients who had been edentulous for longer periods of time had a significantly smaller zone of keratinized mucosa. This work in older overdenture patients supported the results of studies in partially edentulous patients who had implants placed in non-keratinized mucosa (Cox & Zarb 1987; Zarb & Schmitt 1990a, 1990b, 1990c). Taken together, these studies suggested that there was a similar prognosis for implants regardless of whether keratinized or non-keratinized mucosa was present. In a later paper by this same group of investigators, 30 patients with 60 ITI implants and overdentures were evaluated at 3 and 12 months post implant-placement (Mericske-Stern et al. 1995). Approximately 60% of the implants had 1 mm or less of keratinized mucosa on the buccal and lingual aspects of the implant. The results demonstrated that no significant change in width of the keratinized mucosa occurred over the year of follow-up.

Clinical aspects of soft tissues

The value of periodontal probing around endosseous dental implants has been questioned in the literature. In a dog study, histologic assessment of probing around 30 one-stage nonsubmerged implants was evaluated (Lang et al. 1994). After implant placement and healing with frequent plaque removal, the dogs were divided into three groups, including a group with healthy gingiva, a group in which plaque was allowed to accumulate naturally, and a third group in which ligatures were placed around the implants and plaque was allowed to accumulate. Probes were placed after four to six months with a standardized force (0.2 N) and fixed to the mesial and distal surface of each implant. Probe depth was located at the coronal aspect of the connective tissue in healthy tissues, but increased with the degree of inflammation. Probe penetration exceeded the connective tissue level in the ligature-induced group. The authors concluded that probing around nonsubmerged implants was "a good technique for assessing the status of peri-implant mucosal health or disease."

Two other papers have examined periodontal and peri-implant probing. In the first report (Mombelli et al. 1997), 11 patients with teeth and implants were probed to compare tissue resistance and the accuracy of depth determination at different force levels. Better reproducibility around implants was found at higher force levels. A change in probing force had a greater impact on the depth reading around implants compared to teeth. The authors concluded that probing depths around implants were more sensitive to force variation than were probing depths around teeth. In the second report (Christensen et al. 1997), 37 patients were examined with three different automated probing devices. Adequate reproducibility was found with all three probes around both teeth and implants.

Summary

A review of the literature on the supracrestal soft tissues around nonsubmerged endosseous dental implants reveals that many structures and features of non-inflamed supracrestal soft tissues are analogous to non-inflamed gingival soft tissues around teeth. These include a dense, collagenous lamina propria covered with stratified squamous oral epithelium and a non-keratinized sulcular epithelium.

The apical part of the sulcus is lined by a junctional epithelium of typical tooth morphology. Thus, similar to tissues around teeth, the sulcular epithelium appears to be a non-keratinized extension of the oral epithelium and is contiguous with the junctional epithelium. The junctional epithelium is also non-keratinized, provides an epithelial union between the implant and surrounding mucosa, and does not apically proliferate to the bone. The features of these tissues include the features of the same tissues around teeth including basement membranes, rete pegs, connective tissue papillae, collagenous stroma, collagen and non-collagen glycoproteins, desmosomes and hemidesmosomes, structural and non-structural proteins, and immune cells.

Thus titanium – or more accurately, the ever-present titanium oxide – does not appear to alter epithelial cell structures or the formation of epithelial structures around the transgingival portion of the one-piece nonsubmerged Straumann implants, which lack a microgap. These epithelial structures are similar to those around teeth. This suggests that the location of the epithelium (in this case, oral gingival epithelium) is more influential in determining the morphology of the epithelial components than is the substrate (implant versus tooth). Evidence also exists that around the transgingival implant extensions, the major connective tissue fibers run parallel to the long axis of the implant. Around nonsubmerged one-part implants, the connective tissue forms a non-vascularized circular scar-type structure surrounded by a less dense vascularized connective tissue. Thus, the epithelial components around Straumann implants appear to be consistent with epithelial components around teeth, while the connective tissue, although having a similar composition, has a dramatically different spatial orientation. Most importantly, the dimensions of these components around the one-part nonsubmerged unloaded and loaded Straumann implants, histologically comprising a biologic width, are also similar to the biologic width of teeth. It appears that the connective tissue fibers are in direct contact with the implant surface but the ultrastructural nature of this contact is not well understood.

Implant hard tissue integration

Overview

Endosseous implant therapy is dependent on direct contact of the implant with bone. Much of the implant literature has examined the parameters involved in achieving direct bone contact on a predictable basis and under varying anatomical and prosthetic conditions. Bone-to-implant contact can be evaluated in a number of ways. Histomorphometry can determine the extent of bone-to-implant contact, usually expressed as a percentage of a defined surface of the implant. Other studies examining functional characteristics have determined the amount of torque required to remove an implant, or the amount of force required to pull or push the implant out of bone. Many studies have examined ways to increase these parameters. These approaches primarily involve altering the surface and/or shape of the implant.

A complicating factor in studying bone-to-implant contact is that the quality and quantity of oral bone varies greatly within patients as well as between patients. Superimposed on this complexity is the fact that most of the animal models used to study bone-to-implant contact have qualities and quantities of bone that are different than those of humans. However, these studies do allow some comparisons to be made between implants.

Direct contact of the implant to bone

The authors of a review paper on bone-to-implant contact (Listgarten et al. 1991) highlight how the bone-to-implant interface can be described. One reference to an earlier paper describes the intimate contact of bone with the implant surface as 'functional ankylosis', while a later publication is quoted as defining osseointegration as "a direct structural and functional connection between ordered, living bone and the surface of a load-bearing implant. . . ."

By electron microscopic measurement, bone has been observed approximately 20 nm to 40 nm from the surface of the implant and oxide layer (Albrektsson et al. 1985; Albrektsson & Hansson 1986). Consistent with all bone extracellular matrices, this layer was thought to contain chondroitin sulfate glycosaminoglycans. It was further pointed out that studies have indicated that the implant surface has a profound effect on bone apposition, both chemically and physically. In a rat study, for instance, bone formation adjacent to the implant surface was three times faster against a plasma-sprayed titanium surface than against a smoother machined titanium surface (Wilke et al. 1990). In addition, other studies have indicated that the amount of bone in contact with an implant surface is greater around rougher implant surfaces than around smoother implant surfaces and that the strength of the bone-to-implant bond is greater in the rougher-surfaced implants (Carlsson et al. 1988; Thomas & Cook 1985).

Titanium-coated epoxy-resin replicas of cylindrical titanium implants with a TPS surface have been examined by both light microscopy and

transmission electron microscopy (Listgarten 1992). Gingival fibers were found running parallel to the implant surface with no insertions into the smooth or rough implant surface. The innermost connective tissues had no blood vessels, with vascularity increasing in the outer connective tissue zone. Undemineralized and demineralized sections revealed that the bone was intimately adapted to the implant surface, with no intervening space. Occasionally, thinner and less densely packed collagen fibers were observed adjacent to the implant surface, but no fibril-free space could be detected. The authors concluded that "no evidence was found for the presence of a presumptive proteoglycan layer separating the bone from the implant." It is certainly possible that several types of interfaces occur along an implant surface. This is possible since implant placement results in implant apposition to several structures, including soft connective tissues containing fibroblasts, blood vessels and marrow space as well as cortical and cancellous bone.

Surface characterization

A number of studies have compared implants with different surfaces in terms of the hard tissue-to-implant interface. For example, removal torques and bone-to-implant contact measured histomorphometrically were compared around polished and rough commercially-pure titanium implant screws after six weeks in condyles of the rabbit tibiae and femur (Carlsson et al. 1988). The data demonstrated that the rough-surfaced implants had significantly higher removal torque than did the smooth-surfaced implants (26.4 Ncm versus 17.2 Ncm, respectively). The authors stated that "several investigations indicate that a rough-surfaced implant may be a better candidate for implant integration than a smooth implant." They also quoted earlier studies which showed that rough-surfaced titanium implants developed bone contact earlier than smooth implants (Johansson & Albrektsson 1987), and that smooth implants exhibited more fibrous tissue encasement, while similarly-shaped, rough-surfaced implants had more direct bone-to-implant contact (Thomas & Cook 1985; Cook et al. 1987, 1992). The smooth-surfaced implants in this study were electropolished and had surface irregularities of approximately 10 nm compared to implants without electropolishing, which had irregularities of approximately 1,000 nm. The authors concluded that "the present study has demonstrated the importance of the surface roughness for a proper bone interlock."

In a direct comparison of surface characteristics of similarly-shaped implants, rougher implant surfaces had greater bone-to-implant contact than smoother surfaces (Buser et al. 1991a). Seventy-two cylindrical implants with six different surfaces were compared in the metaphyses of the tibia and femur of six miniature pigs at three and six weeks of healing. Electropolished and medium grit-blasted implant surfaces had the lowest percentage of bone contact, in the range between 20% to 25% in the more cancellous pig bone. Large-grit sandblasted implants and titanium plasma-sprayed implants had 30% to 40% mean bone contact, while large-grit sandblasted and acid attacked (SLA) implants (mean 50% to 60%) and hydroxyapatite-coated implants (mean 60% to 70%) had the greatest bone-to-implant contact. However, the HA-coated implants consistently revealed signs of resorption of the surface. The authors concluded that "the extent of bone-implant interface is positively correlated with an increasing roughness of the implant surface."

A subsequent series of studies has confirmed the short-term advantage of the sandblasted and acid-etched (SLA) surface and extended these findings to oral bone, under loaded conditions and for longer time periods. In one study, 69 implants were placed in the canine mandible and implants with an SLA surface were compared to implants with a TPS surface (Cochran et al. 1996). Six foxhounds had the four mandibular premolars and first molar removed bilaterally. The implants with the two surfaces were placed in randomized alternating positions, and four dogs had gold crowns fabricated to mimic the natural occlusion. Standardized radiographs were taken at baseline, preloading, 3, 6, 9 and 12 months post loading. Linear measurements from the implant shoulder to the first bone-to-implant contact (DIB), as well as bone density changes adjacent to the implant surfaces, were evaluated by computer-assisted desitometric image analysis (CADIA). DIB measurements indicated that SLA implants had significantly less bone height loss (0.52 mm) than TPS implants (0.69 mm) at preload and after 3 months of loading. This difference between implant types was maintained after 1 year of loading. Bone density measurements confirmed the crestal bone changes observed in the linear measurements. The authors concluded that "SLA implants are superior to TPS implants as measured radiographically in oral bone under unloaded and loaded conditions."

A histomorphometric analysis of the implants in the study described above confirmed the radiographic findings (Cochran et al. 1998). Histological specimens were evaluated for 2 dogs after 3 months of healing (unloaded group), 2 dogs after 6 months of healing (3 months loaded) and 2 dogs after 15 months of healing (12 months loaded).

The SLA implants had a significantly higher percentage of bone-to-implant contact than did the TPS implants after 3 months of healing (mean±SD: 72.33±7.16 versus 52.15±9.19, respectively) and after 15 months of healing (71.68±6.64 versus 58.88±4.62). No significant difference was found after 6 months of healing (68.21±10.44 versus 78.18±6.81). No clinical differences were observed between the SLA and TPS implants, nor were there qualitative differences in the bone tissue surrounding the implants. The authors concluded that the "results are consistent with earlier studies on SLA implants and suggest that this surface promotes greater osseous contact at earlier time points compared to TPS-coated implants."

These studies confirmed earlier, pivotal work on osseous integration of endosseous implants (Thomas & Cook 1985). In the earlier study, the investigators systematically studied mechanical and histological factors affecting bone apposition to implants. Twelve types of implants were examined after 32 weeks of healing in dogs. Mechanical testing by push-out tests revealed that interface shear strength and stiffness were not significantly affected by implant surface composition. Implant surface texture was the only parameter studied that affected bone apposition. For each elastic modulus group, the rough-surfaced implants had greater strengths than the corresponding smooth-surfaced implants. Histologic evaluation revealed that "the roughened implants exhibited direct bone apposition, whereas the smooth implants exhibited various degrees of fibrous tissue encasement."

Another paper confirmed the advantage of an implant with a rougher surface compared to an implant with a smoother surface (Wennerberg et al. 1995). This study, in rabbit bone, demonstrated that after 12 weeks of healing, a statistically higher removal torque was required to unscrew titanium screw-shaped implants with either a 25 μm (20 implants) or 75 μm (10 implants) aluminum oxide particle-blasted surface compared to a titanium screw (30 implants) with a turned (i.e. machined) surface. In femoral implants, 75 μm particle-blasted surfaces required 32.7 Ncm, compared to 28.6 Ncm for machined-surface implants. With implants placed in the tibia, 35.4 Ncm was required for 25 μm particle-blasted surfaces compared to 29.2 Ncm for machined implants. Histomorphometric analysis over all threads – i.e. the surface of the implant – revealed that greater bone-to-implant contact was found for the 25 μm particle-blasted implant surface than for the machined surface. If only the three best consecutive threads (generally all in cortical bone and thus not reflecting what occurs in cancellous bone areas) were examined, no difference was found between the implants, indicating that this measurement may be misleading if it is the only one taken.

Another study demonstrated that surface roughness and mean spacing of peaks were two surface parameters important for achieving mechanically stable implant fixation (Wong et al. 1995). Three commercially used implant materials were examined, including blasting, high temperature acid etching, and HA coating. Miniature pigs with trabecular knee bone sites had cylindrical implants placed for 12 weeks. An excellent correlation was found (0.90 correlation coefficient) between the average roughness of the implant surface and the push-out failure load.

Another study also found more bone-to-implant contact around rough-surfaced implants (Ericsson et al. 1994a). Standard machined (smooth) screw implant surfaces were compared to titanium oxide-blasted (rough) screw implant surfaces in the maxilla of dogs (Tioblast, Astra Tech) after two and four months of healing. The roughened surface resulted in "surface irregularities smaller than 100 μm." Bone-to-implant contact was measured as the percentage of contact in the three best consecutive threads. The bone-to-implant contact around the rougher-surfaced implants went from 40.5% at two months to 65.1% at four months of healing. The smoother-surfaced machined implants had 39.4% contact at two months and 42.9% contact at four months – a negligible change. The difference between implant types was significant after four months of healing. Qualitatively, bone around both implants appeared histologically similar, with areas of both bone formation and resorption. The authors stated that their results confirmed the findings of others (Buser et al. 1991a; Thomas et al. 1987; Gotfredsen et al. 1992) that implants with a rougher surface have more bone contact than do implants with a smoother surface.

Several papers have been published which have documented biological effects of titanium with various surface characteristics. One paper examined the attachment and growth of human gingival and human periodontal ligament fibroblasts and epithelial cells (Cochran et al. 1994). Titanium with a smooth surface was compared to tissue culture plastic (control) and to titanium with a slightly roughened surface and titanium with a roughened surface. Both fibroblast cell types had more cells attached to the control surface and smooth titanium compared to either of the two rough titanium surfaces. Once attached, the fibroblast cells grew well on both smooth and rough titanium surfaces. Epithelial cells had a typical lag period in their growth after plating on the surfaces and then proliferated on control and

smooth titanium but not on either of the rough surfaces. The data suggested that human fibroblast and epithelial cell attachment and growth are significantly affected by surface characteristics of titanium. The authors speculated that "surface texture could be used to guide specific cell attachment to the dental implant." This is particularly relevant for implants such as the ITI, which is made of one piece and is nonsubmerged so that tissue integration with bone, soft connective tissue and epithelium occurs right from the time of implant placement.

Follow-up studies on titanium with different surface characteristics, conducted by the same research group, have also demonstrated that titanium surface roughness also influences osteoblast proliferation, differentiation, and matrix production *in vitro* (Martin et al. 1995; Kieswetter et al. 1996). These studies revealed that a sandblasted and acid-etched titanium surface (SLA, referred to above) promoted bone cell differentiation, with the cells on this surface having the highest alkaline phosphatase activity. Similar studies have suggested that these effects are also observed with less differentiated and more differentiated chondrocytes (Schwartz et al. 1996). These findings demonstrate that titanium surface characteristics influence a wide range of cell types which are thought to be involved in the tissue integration of transmucosal endosseous dental implants.

Two papers have been published examining the influence of surface treatments of titanium. Five treatment techniques were utilized: mechanical polishing, acid attack in HCl/H_2SO_4, acid attack after mechanical polishing, acid attack after sandblasting (the SLA surface), and titanium plasma-spray (Taborelli et al. 1997; Francois et al. 1997). Surface microroughness, chemical composition and wettability by water were measured in one study (Taborelli et al. 1997). The authors concluded that the different treatments influenced the surface roughness and preserved the chemical composition and wettability properties of the native oxide surface layer. The acid treatment resulted in surfaces with a well-defined micro-roughness either on previously polished or sandblasted surfaces, and covered a hydrogen-rich subsurface overlaid with the usual passivating native oxide layer (Taborelli et al. 1997). Biologically, when fibronectin adsorption was analyzed, surface treatments increasing the surface roughness partly decreased the *in vitro* adsorption of fibronectin (Francois et al. 1997). However, in spite of adsorbing different amounts of fibronectin, both rough and smooth surfaces promoted the normal expression of two functional domains of this extracellular matrix glycoprotein. This latter finding indicates that the cell-binding fibronectin domain is immobilized and well-preserved on the acid attacked titanium surfaces and could be responsible for the enhanced healing observed on this surface *in vivo* (Cochran et al. 1998)

Wilke et al. (1990), in experiments in sheep tibia, demonstrated that the shear strength between bone and a TPS surface is significantly greater than that between bone and a polished surface. In this study, the removal torque values were at least six times higher for the SLA and TPS surfaces than for polished surfaces for healing times of 8 to 52 weeks. Buser et al. (1999) observed the same advantage in a removal torque experiment in the miniature pig maxilla, but at shorter healing times of 4, 8, and 12 weeks. The removal torque for both the SLA and TPS surfaces was more than four times higher than that of a machined surface after 4 weeks of healing, increasing to around ten times after 12 weeks of healing. Another study using the same model has demonstrated a significant advantage of the SLA implant compared to an implant with an acid-only treated surface (Osseotite®). In this study the implant with the SLA surface had significantly higher torque removal values compared to the implant with the acid-only treated surface after 4, 8 and 12 weeks of healing in oral bone (Buser et al. 1998).

The performance of the SLA surface in the studies described above involving both *in vitro* and *in vivo* experimentation provided the supporting evidence that the healing period could be dramatically reduced for implants with an SLA surface. One study has described the early results of two clinical trials established to determine if SLA ITI® solid screw implants could be predictably and safely restored as early as 6 weeks after implant placement surgery (Cochran et al. 2000). The protocols restricted the use of the reduced healing times to healthy patients with sufficient bone volume and good bone quality at the implant recipient site. The first trial was a formal multicenter clinical trial at 6 centers involving 106 patients with 321 implants. Three implants did not integrate. Prosthetic restoration after shortened healing times occurred on 266 implants, with only 2 implants not being able to be restored immediately after abutment placement. The second trial examined, as a field trial, the results from 40 sites in routine clinical practice. There were 362 patients treated with 686 implants. Four implants did not integrate. Restoration occurred after reduced healing times in 551 implants, with 15 implants not able to be restored immediately after abutment placement. Thus, 99% of the SLA implants integrated. Reduced healing time success rates were 99.2% in the clinical trial and

97.3% in the field trial. No implant losses were reported post restoration for up to 18 months in the clinical trial and 12 months in the field trial.

The evolution of traditionally submerged implants to a nonsubmerged placement

Several manuscripts have reported the placement of submerged implants with abutments connected at the first-stage surgery in order to mimic the nonsubmerged technique of implant placement popularized by Dr. André Schroeder and Straumann implants (Becker et al. 1997; Bernard et al. 1995; Collaert & De Bruyn 1998; Ericsson et al. 1994b, 1996, 1997; Levy et al. 1996). Not surprisingly, these implants can achieve success as high as those of implants placed in a submerged approach with abutment connection at a second-stage surgery. These reports simply reinforce the original work, beginning in the late 1960s, of Schroeder et al. (1981), and the concept of Straumann implants that oral implants need not be submerged in order to achieve successful osseous integration. One must be aware, however, when using a submerged implant with an abutment connected, that the crestal bone level (Hermann et al. 1997) as well as the dimensions of the soft tissues surrounding the implant (Cochran & Mahn 1992; Cochran et al. 1997; Weber et al. 1996) may be compromised. The results of Hermann et al. (Hermann et al. 1997, 2000) particularly show that marginal bone loss occurs under these conditions, so that although the two-part system (implant plus abutment) is placed using a nonsubmerged technique, it still has a similar effect on crestal bone (i.e. bone loss occurs) as if it were placed in a submerged technique. Only when the nonsubmerged approach utilizes a one-part implant, or the implant extends above the alveolar crest, is marginal bone height maintained. The former situation is the case with Straumann implants, with a rough surface in the bone and a smooth surface (without a microgap) placed in the soft tissues.

One study of five edentulous patients evaluated implants which are normally placed as submerged implants but which in this study were placed in a one-stage or nonsubmerged technique (Bernard et al. 1995). In these cases the healing abutments, traditionally used at the second-stage surgery, were inserted in the top of the implant instead of the usual cover screw. Mandibular overdentures placed after three months were retained by ball attachments on two implants placed in the canine sites. No problems were reported by the patients or found by clinical or radiographic examination. Bone loss around the implants was similar to that found with a two-stage technique in which the implants were submerged for the initial three months of healing. The authors concluded that "Brånemark fixtures can be inserted using a single-step surgical protocol predictably leading to successful osseointegration and subsequently provide similar peri-implant results as reported for the traditional two-stage technique." The authors further stated that "as it has already been established for ITI implants, the use of a submerged two-stage surgical procedure is not mandatory to achieve osseointegration of Brånemark-type fixtures."

In a study in five Labrador dogs (Ericsson et al. 1996), screw-shaped implants with a machined surface traditionally placed in a submerged two-staged technique were compared to the same implants placed on the other side of the mandible using a one-stage technique (an abutment was connected at the time of implant placement and not loosened or unscrewed for six months). Thus, these were nonsubmerged implants that were two-part – i.e. a microgap existed between the implant and the abutment. Not surprisingly (see Quirynen & van Steenberghe 1993), under these conditions an inflammatory cell infiltrate was observed adjacent to the microgap. An 0.8 mm zone of non-inflamed connective tissue was found between the inflamed tissue and the alveolar crest. The authors concluded that regardless of the surgical technique used, both types of implants lost approximately 2.4 mm of crestal bone and the bone crest was always found 1.1–1.5 mm below the microgap and the apical extension of the junctional epithelium. The authors concluded that "using a dog model, titanium dental implants *ad modum* Brånemark installed according to a one-step or to a two-step surgical procedure will obtain similar soft tissue adaptation and proper bone anchorage (osseointegration)."

Submerged versus nonsubmerged placement

Histological evaluations of tissue reactions to 24 submerged and nonsubmerged titanium plasma-sprayed unloaded implants in six monkeys were made after 22 weeks of healing (Gotfredsen et al. 1991). No differences were found in the bone-to-implant contact between the submerged and nonsubmerged implants. Standardized radiographic data were obtained, and a significantly high correlation was found between the histologic and radiographic data. However, when compared to the histology, the radiographs appeared to underestimate the depth of the infrabony defects. Histologically, both mineralized and non-mineralized areas were observed along the implant surface. On implant surfaces that were surrounded with high percentages of bone, the bone was deposited in layers

with the lamellae parallel to the implant surface. In surface areas without bone, collagen fibers were oriented parallel to the implant surface. SEMs revealed intimate contact between bone and the implant surface, with cellular-rich bony ingrowth into the porosities of the titanium plasma-sprayed surface. Frequently, marginal bone was found up to the coronal extent of the sprayed surface. Histometric analysis indicated that an average of 48% of the implant surface was in contact with bone, whereas 52% was in contact with bone marrow. The authors cautioned against comparing the percentage of bone-to-implant contact between published studies due to many factors, including great differences between animals, anatomic sites, regions and loading conditions, trabecular pattern, and ratio of cortical to cancellous bone. This paper concluded that no significant difference occurred between submerged and nonsubmerged implants placed in similar sites in the same animal with regard to bone-to-implant contact, suggesting that "osseointegration" could be established in one-stage as well as two-stage procedures.

In another study (Fartash et al. 1990), single-crystal aluminum-oxide (sapphire) implants placed nonsubmerged in two beagle dogs were examined with light microscopy, scanning and transmission electron microscopy after six months of unloaded healing. These investigators found most of the implant in direct contact with bone in the coronal cortical areas, with more bone marrow and cancellous bone contact in the more apical portion of the implants. The average bone-to-implant contact was 61.8% of the surface. No osteoclasts or signs of inflammation were observed. Mandibular sections revealed Haversian systems and interstitial bone. The authors concluded that "comparison between one-stage and two-stage dental implants shows no obvious differences in the direct bone-implant contact area."

A pilot study in monkeys with unloaded and loaded nonsubmerged implants confirmed the findings above (Piattelli et al. 1993). These investigators used histological techniques and concluded: "This study confirms recent clinical and experimental research and further suggests that implants do not have to be left submerged for a given period in order to achieve direct bone apposition with no intervening connective tissue."

An ultrastructural study of ceramic and titanium screw-shaped implants also confirmed the similarity of bone-to-implant contact of one- and two-stage implants (Steflik & McKinney 1989). Dogs were utilized and half of the 32 implants were loaded with fixed bridgework. Radiographic and histologic analysis did not reveal significant differences between the implants in the study. The authors concluded that "one-stage endosteal implants are capable of maintaining a proportional bone-to-implant interface at the apical support region, similar to that suggested for two-stage implant systems."

A further study in 4 beagle dogs compared 12 submerged implants placed on one side of the mandible to 12 nonsubmerged implants placed on the other side of the mandible (Levy et al. 1996). Histological analyses were performed after six weeks of healing. The authors concluded that implants which are traditionally placed in a submerged two-staged approach "can also become successfully integrated using a 1-stage approach...". Their findings support the discussion above on the evolution of submerged implants to a nonsubmerged placement similar to Straumann implants.

Retrieved implants

Studies on implants retrieved from patients have revealed direct bone-to-implant contact. Histologic examination of an ITI hollow cylinder implant after four years of function was reported in a human case report (Gratz et al. 1994). Clinically, the implant was successful and histologically, healthy bone was found in the perforations of the implant, with intimate bone contact around the implant surface. The authors reported "a direct connection of histologically mature bone to the implant without an interface layer." Another case report examined tissues obtained by autopsy from areas surrounding three ITI implants (one implant having been placed in an area of insufficient bone) after a 10-month loading period (Piattelli et al. 1997). No inflammation was observed in the epithelium and supracrestal connective tissues, while connective tissue fibers were found running in a parallel direction along the machined coronal portion of the implant and in a perpendicular direction along the more apical TPS implant surface. Histologically, areas of direct bone contact were noted, as well as areas of unmineralized tissues resembling osteoid. Bone had formed within the hollow central portion of the implants. These results confirmed a case report examining three implants that were removed due to coronal bone loss (Takeshita et al. 1997). Histologic examination demonstrated that the average bone-to-implant contact was 93.1%, 90.9%, and 84.3% for the three implants. Interestingly, the hollow portions of all the implants were almost all filled with bone tissue. Another report by this group of investigators examined failed hollow implants where four of the five implant types were various Straumann implant designs (Takeshita et al. 1996). The authors concluded that "the pres-

ence of an empty basket may cause fracture of the basket portion," and suggested that hollow implants should not be used in specific indications such as immediate implant placement cases.

Implant integration with a ligament

In a review article that compared periodontal tissues to peri-implant tissues, periodontal ligament tissues were discussed, as was the question of why a ligament was usually not found around endosseous implants (Listgarten et al. 1991). It was suggested that the lack of cementum was not due to an inability of cementum to form on titanium, but rather that it was due to a lack of cementum progenitor cells in the implant site. Cementum progenitor cells appeared to be derived from periodontal ligament, so without this source of cells, a ligament could not form around an implant. In interesting examples that reinforced this concept, three publications demonstrated that if an implant was placed adjacent to a root tip, an attachment apparatus similar to that around teeth was found (Buser et al. 1990b, 1990c; Warrer & Karring 1993). This was attributed to the fact that progenitor cells from the periodontal ligament were present, became stimulated, and formed cementum and ligament proper on the titanium surface. This was a particularly intriguing finding for the field of Periodontology, as it suggested that the substrate – i.e. the surface – was not the critical factor for the formation of a ligament. At present, the desirability of an endosseous implant with a ligament is unknown. Experiences with fibrous encapsulation should not, however, be used as an analogy, since a ligament with Sharpey's fibers is a functional structure and fibrous encapsulation is not. Other studies confirmed the findings above (McKinney et al. 1988; Steflik et al. 1993).

Crestal bone levels

The evaluation of crestal bone levels has become a critical component of implant success or failure criteria. Over the years, both submerged and nonsubmerged implant designs have been examined in preclinical and clinical models. From these investigations, it is clear that both implant types perform well. However, with submerged implants, the location of the microgap and, for both types of implants, the characteristics of the surface play a role in the final position of the crestal bone level.

An important recent study examined the crestal bone levels around submerged and nonsubmerged implants in a six-month side-by-side comparison using standardized monthly longitudinal radiographic analysis (Hermann et al. 1997). Fifty-nine implants were placed at different levels to the alveolar crest in the mandibles of five foxhounds, with half the implants placed in a nonsubmerged technique and half in a submerged technique with abutment connection three months later. Linear measurements analyzed the distance between the top of the implant/abutment and the most coronal bone-to-implant contact (DIB). Bone density changes were determined using computer-assisted densitometric image analysis (CADIA). DIB measurements revealed that in one-part nonsubmerged implants the most coronal bone-to-implant contact followed the rough/smooth interface at all time points. In all two-part implants, regardless of whether they were submerged or nonsubmerged, the most coronal bone-to-implant contact was consistently located approximately 2 mm below the interface between the components (i.e. microgap). CADIA measurements of density in the coronal bone tissue adjacent to the implant confirmed the linear measurements. All bone changes were statistically significant and detectable one month after implant placement in nonsubmerged implants or one month after abutment connection in submerged implants. These findings suggest that crestal bone changes are correlated with the presence of a microgap even when a two-part implant (i.e. implant plus an abutment) is placed in a nonsubmerged technique. In further support of the correlation of a microgap with crestal bone changes, if the microgap was placed above the bone crest, less remodeling occurred, whereas when the microgap was placed below the bone crest, greater amounts of bone loss were observed. The investigators concluded that "the rough/smooth implant interface as well as the location of the microgap have a significant effect on marginal bone formation as evaluated by standardized longitudinal radiography." These findings are particularly significant in that they support an earlier study that suggested that a biologic width forms around implants that is physiologically determined, stable, and similar to the dimensions around natural teeth (Cochran et al. 1997). These findings also provide an explanation for the 1.5 mm bone loss observed around submerged implants (when a microgap is created after abutment connection at second-stage surgery) in the first year of function; this bone loss pattern has gained general acceptance as a success criteria for certain submerged screw-type implants.

Another paper described the histological findings for the first bone-to-implant contact in the experiment described above (Hermann et al. 2000). The results indicated that for one-piece nonsubmerged implants (types A and B), mean crestal bone levels were located adjacent (within 0.19 mm)

to the rough/smooth border. For two-piece implants (submerged implant plus an abutment), whether placed in a nonsubmerged technique (the abutment was connected at first-stage surgery) or in a submerged technique (the abutment was placed at second-stage surgery), crestal bone loss of 1.68 mm or 1.56 mm, respectively, occurred below the implant/abutment interface (microgap) which had been originally placed at the alveolar crest level. If the interface between submerged implant and abutment (placed at second-stage surgery) was moved coronally 1 mm from the alveolar crest, the bone was located at the rough/smooth interface, therefore not being influenced by the interface (microgap). If the interface (microgap) was located originally 1 mm apical to the alveolar bone crest after abutment connection on the submerged implant, significant (2.25 mm) crestal bone loss occurred. The bone loss, which occurred around the implants in this latter situation, was significantly greater than the bone loss which occurred around the other five implant types. Thus these findings confirmed the radiographic findings in this animal study. The radiographic and histologic studies combined indicate that crestal bone changes are dependent on the surface characteristics of the implant and the presence/absence as well as the location of an interface (microgap). Interestingly, crestal bone changes were not dependent on the surgical technique (submerged or nonsubmerged).

One study evaluated the clinical effect of placing standard ITI implants in a slightly apical position such that the border between the TPS surface and the 3 mm transmucosal machined portion of the implant was 1 mm below the alveolar crest (Hämmerle et al. 1996). This report involved 11 patients requiring 2 implants, where one implant was placed with the rough/smooth interface at the bone crest level to serve as a control and the second implant was placed with the rough/smooth interface 1 mm below the marginal bone level. Bone loss was observed under both conditions during the first four months, with the test implants continuing to lose bone during the subsequent eight months. The control implants did not lose bone from 4 to 12 months post implant placement. After one year the test implants had a bone level an average of 0.38 mm more apical than the control implants. These findings confirmed the results on crestal bone remodeling around one-piece nonsubmerged implants in the study described above (Hermann et al. 1997). No significant differences in the clinical findings occurred between test and control implants except for the gingival index at four months post placement. Because the implants in this study were placed with a difference of 1 mm between test and control, and after one year only 0.38 mm difference in bone remodeling was detected radiographically, the clinical significance of the difference in implant placement is not clear, and depending on specific clinical indications may in fact be warranted. This point was reinforced by the fact that no lasting significant clinical findings occurred with the more apical placement of the standard ITI implant in this study.

Summary

The direct contact between bone and an implant surface describes a morphological condition (Steinemann et al. 1986). This situation has been named ‘osseointegration’ or ‘functional ankylosis’. Both of these terms are often used incorrectly to clinically describe an implant. It must be remembered that these terms refer to a histological phenomenon and that clinically the implants are not mobile and have no continuous periapical radiolucency, both of which are appropriate clinical and radiographic descriptions, respectively. The placement of an implant in oral bone almost always involves contact with both cortical and cancellous bone and provides primary stability. During the healing period, primary stability is converted into a functional stability.

A number of experiments have tested ways to increase the support of implants in bone tissue by modifying the surface characteristics of the implant. Rougher implant surfaces have almost universally been shown to have more bone contact and require greater forces to be displaced than smoother implant surfaces. These results may vary somewhat over different time periods, models, and clinical conditions, but the results to date are consistent and are supported by the studies on retrieved human implants.

The data reviewed above also demonstrate that both submerged and nonsubmerged implants can achieve osseous integration. Additionally, the presence of an interface (microgap) between an implant and an abutment influences the location of the osseous crest no matter whether the implant is placed in a submerged or nonsubmerged technique. Because bone is a dynamic, well-vascularized tissue, no implant achieves 100% contact with bone, and vascular elements and soft tissue contact the implant within the bone tissue. It appears that almost all endosseous implants that are used clinically can achieve bone contact at the light microscope level, given ideal bone, surgical, and clinical conditions.

The findings and discussion above permit a more enlightened view of implant integration in bone. It is now obvious that, in addition to quan-

tity, both the quality and the location of 'functional ankylosis' or 'osseointegration' on an implant surface are of critical importance in determining the biomechanics of implant integration. Analysis of biomechanical strength includes resistance to forces such as removal torques, push and pull-out strengths, etc. For these reasons, it is proposed that the terms 'functional ankylosis' and 'osseointegration' be restricted to use as they were defined – i.e. to histologically describe direct bone-to-implant contact at the light microscope level. Thus, clinical integration of an implant is dependent on more than direct bone-to-implant contact, and other factors must be taken into consideration, such as the amount, location, and quality of the supporting bone structure, the soft connective tissues and the epithelium.

Predictability of Straumann implants

Overview

Many studies have been published on the use of dental implants in patients, both retrospectively and prospectively. Most of the papers are longitudinal descriptions of the authors' clinical experience with a certain implant or implants and in one or several types of indications/restorations. Use of endosseous implants has been reported for almost every conceivable clinical situation. One aspect lacking in this area is a definition of what constitutes 'long-term' versus 'short-term' follow-up. No precise definitions are available, and trying to create them would not be particularly beneficial. Similarly, strict definition of implant 'success' or 'failure' for all these studies is not particularly useful, because those cases which qualified as 'successes' in one particular clinical situation may not be considered successful in a different clinical indication. It is more important to report on all the implants placed, without exclusion, so that the reader can better understand the complete experience of the authors. This is particularly true for these clinical articles, as they are longitudinal descriptions and not randomized, controlled, blinded clinical trials. For this reason, prospective studies that report all experiences are more significant than retrospective reports that do not include all experiences. Many peer-reviewed studies have documented the success rates of Straumann dental implants (Tables 1–4).

Experiences in the treatment of completely edentulous patients

Treating edentulous cases with removable overdentures (traditionally retained by clips or ball attachments) is an alternative to the fixed "removable" overdenture in which the denture is screwed into the implants and does not allow the patient to remove the appliance. Some patients prefer being able to remove their dentures, and with removable overdentures it is often the case that fewer implants can be placed, which reduces the cost of the treatment. If fewer implants are utilized, such as two implants that are used with or without a connecting bar, the denture is usually implant- and tissue-supported and can result in soft tissue effects. The screw-retained appliances, which rely on more implants, allow the denture to be totally implant-supported. For this reason, screw-retained restorations have less effect on the oral soft tissues.

One group of investigators published a prospec-

Table 1. Peer-reviewed studies 1984–1991

Author	Center	Patient/ implant #	Type of implant	Primary indication	Max. time follow-up	Success rate
Ledermann 1984	Switzerland	146/500	TPS screw	Edentulous mandible	6.5 y	91.6%
Babbush et al. 1986*	US Switzerland Germany Sweden	484/1739	TPS screw	Edentulous mandible	8 y	88.0%
Krekeler et al. 1990	Germany	201/754	TPS screw	Edentulous mandible	9 y	88.3%
Mericske-Stern 1990*	Switzerland	62/153	HC	Edentulous mandible	5.5 y	95.4%
Van Beek & van Gool 1991	Netherlands	270/745	HS HC SS	Edentulous mandible	8 y	97.2%

* Indicates use of lifetable analyses
HC=Hollow cylinder; HS=Hollow screw; SS=Solid screw; y=years.

Table 2. Peer-reviewed studies 1991–1994

Author	Center	Patient/ implant #	Type of implant	Primary indication	Max. time follow-up	Success rate
ten Bruggenkate et al. 1991	Netherlands	156/431	HC HS SS	Partial & fully edentulous mandible & maxilla	2.5 y	99.0%
van Gool et al. 1992	Netherlands	841/2454	HC HS SS	Partial & fully edentulous mandible & maxilla	9.5 y	98.0%
Buser et al. 1992b*	Switzerland	126/249	HS HC	Partial & fully edentulous mandible & maxilla	5 y	95.8%
Mericske-Stern et al. 1994	Switzerland	33/66	HC	Edentulous mandible	5 y	96.9%

* Indicates use of lifetable analyses
HC=Hollow cylinder; HS=Hollow screw; SS=Solid screw; y=years.

Table 3. Peer-reviewed studies 1995–1996

Author	Center	Patient/ implant #	Type of implant	Primary indication	Max. time follow-up	Success rate
Wismeyer et al. 1995	Netherlands	64/218	TPS screw	Edentulous mandible	9.5 y	96.8%
Donatsky & Hillerup 1996	Denmark	40/156	HS	Edentulous mandible	3 y	99.0%
Astrand et al. 1996	Sweden	46/216	HS	Edentulous mandible	2 y	96.2%

HS=Hollow screw; y=years.

Table 4. Peer-reviewed studies 1997

Author	Center	Patient/ implant #	Type of implant	Primary indication	Max. time follow-up	Success rate
Ellegaard et al. 1997*	Denmark	56/93	HS	Partial maxilla	7 y	95.0%
Levine et al. 1997	US	129/174	HC HS SS	Single crown (maxilla & mandible)	0.5 y	97.7%
Nishimura et al. 1997	Japan	12/32	SS	Partial mandible	4 y	100%
Chiapasco et al. 1997	Italy Switzerland	NA/460	TPS screw HS	Edentulous mandible	9 y	98.0%
Behneke et al. 1997*	Germany	109/320	SS	Partial & fully edentulous mandible & maxilla	3 y	97.1%
Buser et al. 1997*	Switzerland Germany	1003/2359	HC HS SS	Partial & fully edentulous mandible & maxilla	8 y	93.3%

* Indicates use of lifetable analyses
HC=Hollow cylinder; HS=Hollow screw; SS=Solid screw; y=years.

tive five-year study of 33 edentulous patients treated with two ITI nonsubmerged implants and an overdenture supported by a connecting bar or single spherical attachments (Mericske-Stern et al. 1994). All implants were clinically stable at the time of loading. A total of two implants failed in the study after loading (97% success). One implant had a peri-implant lesion after two years, the other a fracture after four years. Minimal to no loss of attachment was noted and pocket depths averaged about 3 mm. Approximately 50% of the implants were placed in non-keratinized mucosa, but no adverse affects were found compared to implants placed in keratinized mucosa. If greater than 2 mm of keratinized tissue was present on the buccal surface, there was a tendency for decreased bleeding over the five-year period. If patients had been edentulous for more than five years, significantly less attachment loss occurred around the implants. The authors concluded that "advanced age, reduced dexterity of elderly patients, and environmental conditions of overdentures do not represent a higher risk for the development of peri-implant lesions..." and that elderly patients can be maintained with healthy tissues around their implants for five years, regardless of the presence or absence of keratinized mucosa or the length of time the patient was edentulous before implant surgery.

In an earlier retrospective study by the same investigators, 67 edentulous patients had two ITI implants placed (Mericske-Stern 1990). A clip over a connecting bar was used to attach the overdenture in 29 patients, and individual ball-shaped precision attachments were used in 27 patients. A control group of 11 patients had three to four implants placed that were splinted with a bar. All patients received new complete dentures six months prior to implant placement and patients were followed for up to 66 months. Keratinized gingiva was present in approximately one-half the buccal and lingual sites. Two implants were lost after overdenture insertion. In this cross-sectional study, the authors concluded that two implants could provide support for a complete mandibular denture and that attached gingiva was not a prerequisite for success. The authors stated that multiple implants or splinting of implants was not necessary for overdenture retention, and that "the connection of overdentures to only two implants by a single attachment is a practical, easy, and economical method, especially when implant surgery follows prosthodontic treatment." It was noted, however, that ball-shaped attachments did not always provide adequate retention for patients with severely resorbed ridges.

Another study investigated the use of 216 nonsubmerged ITI dental implants in edentulous mandibles of 46 patients (Astrand et al. 1996). The patients were followed for 2 years and received either a fixed prosthesis or an overdenture restoration. Four implants were lost as early failures before implant loading and four implants failed during the second year of function, yielding a survival rate of 98% after 1 year and 96% after 2 years. No significant marginal bone loss was observed for the first year of function, confirming an earlier study (Buser et al. 1991b) of Straumann implants. A mean loss of 0.1 mm was recorded. The bone change around 155 of the 204 implants ranged from +0.5 mm to -0.5 mm, indicating that the majority of implants had essentially no change in marginal bone levels. Twenty implants demonstrated a gain of marginal bone and four implants showed severe bone loss. The authors concluded that the data "corroborate experimental studies showing equal or better results of the nonsubmerged technique (Weber et al. 1996; Gotfredsen et al. 1991; Gotfredsen et al. 1990)."

A prospective study examined 156 ITI implants in 40 patients with advanced mandibular ridge atrophy (Donatsky & Hillerup 1996). Hollow screw implants with ball attachments were used to support overdentures that were delivered 3–4 months after implant placement. Recall ranged from 1 to 3 years, with an overall implant success rate of 99% (155 successful implants out of 156). All the prostheses were functional throughout the study (100% success rate). These investigators concluded that "nonsubmerged osseointegrated ITI-Bonefit dental implants with ball attachments supporting overdentures can be a successful alternative to combined vestibulo-lingualplasty with free split-thickness skin graft and removable dentures, and as successful as the use of submerged dental implants."

One study retrospectively analyzed IMZ and TPS (Straumann) implants placed in edentulous mandibles and restored for up to 11 years with overdentures retained by bars (Spiekermann et al. 1995). One hundred thirty-six patients (68.4% female) were treated with 300 implants. A greater than 90% success rate (by life table analysis) was recorded for all the implants, based on five-year survival rates. With a failure defined as an implant having 4 mm or greater bone loss, the implant system survival rates for the five-year period ranged from 83% to 97%, depending on the implant system. In this study, the TPS screw implants were one-stage and could be loaded immediately. Three IMZ implants were utilized. Radiographic assessments were made from panoramic radiographs and as such must be interpreted with caution, as the authors noted. Pocket depths around all implants decreased over time, with the one-stage TPS im-

plant having the smallest pocket depth and the least marginal bone loss. Interestingly, when the data from this study were combined with those from an earlier study by the same investigators, a low correlation coefficient ($r=0.27$) (Spearman) was found between bone loss and pocket depth, which suggested that pocket depth was of little value in determining implant osseous support. Additionally, the data indicated no correlation between width of attached gingiva and implant success. As stated by the authors, marginal bone loss was greater (0.54 mm/year) compared to the Brånemark data, but the authors cited an earlier paper (Naert et al. 1988) stating that the Brånemark implant data "exclude bone loss occurring in the first year and perform certain data selection." Standard deviations of 0.2 to 0.5 mm/year were reported, with 47% of measurements being greater than 0.1 mm (van Steenberghe et al. 1993). The authors (Spiekermann et al. 1995) concluded that their results indicated that "solid one-piece implants, such as the TPS screw-type implant, show better results than IMZ implants with polyoxymethylene TIE."

An early report was published on a TPS Swiss Screw implant (Straumann implants) study which examined 484 patients, treated in four countries, followed over a four- to eight-year period (Babbush et al. 1986). As noted above, this implant is a nonsubmerged (i.e. one-stage) type and was designed to be placed in the mandibular symphysis area anterior to the mental foramen and loaded within a few days with a bar and clip removable overdenture. In the 484 patients treated, 1,739 implants were placed, with 94.08% (life table analysis) still functioning 8 years later. In all four countries, over 90% of the implants placed were reported in function even after immediate loading. The authors concluded that the success rates for the TPS Screw Implant System "exceed established guidelines and recommendations for a successful dental implant."

A multicenter retrospective study using four implant types evaluated immediately placed mandibular overdenture restorations in 226 consecutive patients (Chiapasco et al. 1997). Two of the implant types utilized were Straumann implants (TPS and ITI implants). A total of 904 implants were placed in the mental symphysis area so that each patient received 4 implants. A total of 194 implants were followed from 2 to 13 years. The overall success rate was 96.9% (24 of 776 implants failed). The authors concluded that "the success rate of immediately loaded implants is similar to that obtained in the case of delayed loading, after osseointegration has taken place."

Another study has reinforced early implant experiences with the TPS screw where restorations were placed on implants immediately or within the first couple of weeks after implant placement (Tarnow et al. 1997). Four different implant systems were used, including ITI dental implants. The 10 patients treated in this report all had a fixed provisional restoration following implant placement, and the authors concluded that "immediate loading of multiple implants rigidly splinted around a completely edentulous arch can be a viable treatment modality."

Experiences in the treatment of partially edentulous patients

One study prospectively reported on 54 one-stage, nonsubmerged ITI implants in 38 partially edentulous patients (Pham et al. 1994). The observation period for the 54 implants was three years. A 96.2% overall success rate was reported, with two implants as late failures with recurrent infections. No early failures were reported. Pocket depth increased slightly from the one-year examination (2.81 mm) to the three-year examination (3.14 mm). Mean attachment levels went from 2.68 mm to 2.95 mm. Importantly, the mean bone level around all 51 implants was stable over the three-year period. At the one-year examination, the success rate was 98.1%. The authors concluded that "the intentionally nonsubmerged placement of ITI implants does not jeopardize successful tissue integration." Furthermore, the integration was maintained over three years. Interestingly, a higher failure rate in the maxilla was not found in this study and the prognosis was the same for the implants placed in the maxilla as in the mandible.

One report retrospectively evaluated ITI implants used by 12 United States clinicians for single-tooth restorations (Levine et al. 1997). In this study, 174 implants were placed in 129 patients, with the most implants (86.8%, or 151) placed in the posterior. Ninety-four implants were placed in molar sites, with 75 in the mandible and 19 in the maxillary arch. Radiographic analysis showed no failures in any of the maxillary molar implant sites and three failures in mandibular molar sites, for a 96.8% success for molar sites. Twenty-three implants were placed in the anterior. Slightly over half (54.6%) of the implants in this study were 10 mm or less in length. The survival rate for these implants was 97.7% after six months. Ninety-two implants had screw-retained restorations and 82 implants had cemented restorations. Screw loosening occurred in 8.7% of the implants, with no repeated loosening. One patient had an abutment loosen. Radiographic analysis revealed significant bone loss around 2.3% of the implants. The authors concluded that "ITI implants can be

a satisfactory choice for posterior single tooth restorations." These findings are of particular interest due to the relatively short lengths of the implants used, the number of implants placed in the posterior, the number of implants placed in the maxilla, the fact that one implant was used to replace molar teeth, and the low occurrence of screw and abutment loosening.

Another study evaluated the results of implants placed in periodontally compromised patients in a private practice (Ellegaard et al. 1997). Ninety-three ITI dental implants and 31 Astra implants were placed in 75 patients. The majority of the implants (94/124) were placed in the maxilla and mostly in the posterior. There was an observation time of up to 7 years for the ITI implants and 40 months for the Astra implants. Three ITI implants failed, yielding a 95% three-year ITI implant survival rate. The authors concluded that nonsubmerged implants can be maintained in patients with a previous history of periodontitis for a period of three to five years, with 95% of the ITI implants surviving for 5 years by life table analysis. Interestingly, the maxillary implants had a survival rate of 97% at three years for these rough-surfaced implants.

Experiences in patients requiring implant treatment in multiple indications

A long-term multicenter evaluation of ITI implants has been published documenting 2,359 nonsubmerged implants in 1,003 patients (Buser et al. 1997). Seven hundred and fifty-eight fixed and 393 removable restorations were utilized. Eight-year life table analysis was performed in this prospective study to obtain cumulative survival and success rates. Thirteen implants failed prior to loading, yielding an early failure rate of 0.55%. Nineteen implants failed in the follow-up period, with 17 implants having infections at the last examination. The 17 implants – or 0.8% of the implants in the study – represent an extremely low frequency of peri-implant infections with a rough endosseous implant surface. This observation indicates that the TPS surface used in the apical portion of the implant to enhance bone anchorage does not place the patient at risk of developing implant infections. The eight-year cumulative survival and success rates were 96.7% and 93.3%, respectively. Cumulative success rates were >95% for screw-shaped implants and 91.3% for hollow cylinder implants. Mandibular implant success rates were approximately 95%, with maxillary implants having a lower success rate of 87%. Similar results were found between anterior and posterior regions within the same arch (cumulative success rates at eight years for the anterior and posterior mandible were 94.1% and 95.4%, respectively; rates for the anterior and posterior maxilla were 87.8% and 86.7%, respectively). Three implants fractured in this study of 2,359 implants, with the fracture occurring after bone loss reached the first row of perforations of the implant body. The 4.1 mm diameter solid-screw implants never fractured in this study, nor have there ever been any reported fractures for this implant in other studies. No significant difference in success rates was found between 8 mm (91.4%) and 12 mm (95.0%) long implants, in spite of the fact that the majority of the 8 mm implants were placed in the posterior portion of the mouth. The actual five-year survival and success rates of 488 implants were 98.2% and 97.3%, respectively. These actual values were slightly higher than the estimated five-year cumulative rates, indicating that the applied life table analysis is a reliable and conservative statistical method for evaluation of the long-term prognosis of nonsubmerged ITI implants. The authors concluded that "nonsubmerged ITI implants maintain success rates well above 90% in different clinical centers for observation periods up to 8 years." These findings applied for both the eight-year survival and success rates of the original 2359 implants as well as for the actual five-year survival and success rates of 536 implants.

Another study has demonstrated a cumulative survival rate of 96.2% after a 10-year life table analysis of 1,475 implants in fully and partially edentulous patients (Buser et al. 1999). By applying strict criteria of success in this study, a 10-year cumulative success rate of 91.4% was calculated. The favorable clinical results for long-term stability were also confirmed by overall stable bone crest levels on 97 implants for 8 years. The mean alveolar bone loss between the one-year and the eight-year examinations only differed by 0.03 mm. In fact, more implants gained bone than lost bone, with 72 of 97 implants having one-year to eight-year bone changes ranging between -0.7 mm and $+0.7$ mm. Thus both clinical and radiographic long-term evaluation indicate highly successful and predictable use of ITI dental implants.

As was described above, much success of the ITI dental implants has been attributed to the use of the TPS and SLA surfaces. One paper has recently examined publications of human clinical experiences evaluating implant use in patients to determine if differences existed in success rates of implants with relatively smooth surfaces compared to implants having roughened implant surfaces (Cochran 1999). When studies were clustered by specific indications or patient populations, rough-surfaced implants, when all implants were con-

sidered, had significantly higher success rates compared to implants with more smooth surfaces, except in the case of single-tooth replacements, where the success rates were comparable. In general, implants placed in the mandible had significantly higher success rates than did implants placed in the maxilla. In the partially edentulous patient group, titanium implants with a rough surface had significantly higher success rates in the maxilla compared to the mandible, and in cases of single-tooth replacement, success rates were similar in the maxilla and in the mandible, as was the case for hydroxyapatite-coated implants. Thus, the documented advantage of implants with a roughened surface in animal and *in vitro* experiments was demonstrated in clinical cases when studies were compared where specific indications or patients were treated. These meta-analyses further support the advantage of ITI dental implants with TPS or SLA surfaces.

One paper described the use of a one-part implant system (a nonsubmerged implant and abutment made as one piece, such as the TPS or Swiss Screw) and a newer design, a two-part implant system in which the first part was the nonsubmerged transmucosal implant and the second part was the abutment that fit inside the orally-exposed implant (Buser et al. 1992b). This latter design placed the microgap between implant and abutment either supragingivally or only slightly subgingivally, but always well above the osseous crest. These investigators treated 25 patients with atrophic edentulous mandibles using 95 one-part ITI implants. These implants were intended for use in edentulous mandibles as retentive anchors for bar-type overdentures and the bar was attached to the implants within 24 hours. No early failures were reported and three late failures were reported (96.9% success rate) in 33 months of follow-up. Clinically, the failed implants had acute infections, purulent exudates, poor hygiene, and bone loss. Sixty-seven patients were treated with 88 two-part ITI implants. No early failures were reported with these implants placed as single teeth or in partially edentulous areas. One late failure after two years was reported (98.9% success rate). This implant presented with an acute infection and was treated successfully with metronidazole. No other surgical or prosthetic complications were reported. Overall, 183 implants were placed, with four late failures and a 97.8% success rate. The authors concluded in this early study that it was not necessary to submerge an implant in order to achieve osseous integration for the titanium plasma-coated implants studied.

Another report examined 32 solid-screw ITI implants in the mandibles of 12 patients over a four-year follow-up period (Nishimura et al. 1997). The overall implant success rate was 100%, with no signs of inflammation, radiographic bone loss or mobility over the four years. Mean probing pocket depth was 2.09 mm at 48 months, confirming the findings of an earlier study (Buser et al. 1991b). Loss of attachment was observed to decrease over time (probing attachment levels at 48 months had a mean of 2.55 mm), indicating that the marginal bone was stable and in fact improved over time. Standardized radiographs confirmed this finding, with a mesial and distal implant shoulder to bone crest distance of 3.5 mm after 6 months and 3.5 ± 0.6 mm (SD) after four years. Considering the 3 mm transmucosal portion of the implant, this corresponds to approximately 0.5 mm of marginal bone loss over the first six months and a stable marginal bone level for up to three and a half years of recall.

Twelve ITI implants placed in regenerated bone were evaluated in a prospective study with a five-year follow up (Buser et al. 1996). All 12 implants were successfully integrated and stable over the five-year period. Stable marginal bone crest levels were observed, with a mean bone loss of 0.30 mm between the one-year and five-year evaluations. Between the time of implant placement and the one-year exam, approximately 0.5 to 1.0 mm of marginal bone loss occurred. Two implants revealed bone loss greater than 1 mm during this observation period. The investigators concluded that "bone regenerated with the membrane technique reacts to implant placement like non-regenerated bone" and "this bone is load-bearing, since all 12 implants maintained osseointegration over a 5-year period."

Summary

Many experiences with nonsubmerged endosseous Straumann dental implants have been published that document highly successful short- and long-term clinical use. Within the Straumann implant system, and with most other implant systems, changes have occurred over time. Some conclusions can be drawn from the longitudinal studies reviewed above. Submerged and nonsubmerged implants demonstrate similar overall clinical success rates by longitudinal descriptive clinical analysis. Better implant success rates may exist for mandibular implants than for maxillary implants, although some reports suggest no differences in success rates. Overall success rates in partially edentulous arches do not appear to be significantly different than the overall success rates in totally edentulous arches. It appears that placing implants in mucosa that was not keratinized does not put them at higher risk. Stable bone levels have been demonstrated around the nonsubmerged titanium plasma-sprayed Straumann dental implants.

Conclusion

A review of the literature on the scientific basis for and the clinical experiences with Straumann dental implants including the ITI® Dental Implant System has been presented and permits the following conclusions to be drawn. The titanium plasma-sprayed surface applied to the commercially pure grade IV titanium implants has been extensively studied and documented for well over 20 years. The SLA implant surface has also been extensively studied, and human clinical experiences reveal extremely high success rates consistent with or better than reports on implants with other surfaces. These rates are particularly impressive considering that the implants are generally restored after 6 weeks of healing. These surfaces have been shown to promote enhanced integration with bone tissue compared to machined and other smoother dental implant surfaces. In animal and human clinical studies, no adverse reactions have been found with these implants compared to other implants described in the literature. The nonsubmerged one-piece design of the implant used over the same time period (greater than 20 years) has set a proven standard in implantology, and a trend can now be documented in current implant therapy as other dental implants are being manufactured with similar designs and placed using nonsubmerged techniques. The nonsubmerged one-piece design of the ITI dental implant offers unique advantages compared to other designs incorporating multiple components with connections (interfaces or microgaps) at or below the alveolar crest. Foremost among these advantages are the histological dimensions of the soft tissues around the implant comprising the biologic width similar to the same dimensions around teeth, and the lack of microbial contamination between components at the alveolar crest. Connection of components at or below the alveolar crest has been shown to result in bone loss.

Light and electron microscopy document the intimate contact of bone, soft connective tissue and epithelium with the implant surface. The morphological features of the epithelium around the ITI implant are similar to those around natural teeth. A connective tissue contact is found which is circular in nature and avascular immediately adjacent to the implant surface. Inflammatory reactions in these tissues appear to be similar to reactions found in the same tissues surrounding teeth. The presence of keratinized mucosa does not appear to be a prerequisite for implant success.

The clinical success of Straumann implants and the ITI® Dental Implant System has been extensively documented. This documentation includes retrospective and prospective studies, studies incorporating life table analyses, multicenter and multi-country experiences, evaluation by strictly defined criteria and in all areas of the mouth with various restorative techniques. In all the studies evaluated, steady-state levels of the implants are achieved clinically and radiographically, as the few reported complications observed with all endosseous dental implants decrease with time. Reports on implants with a sandblasted and acid attacked surface (SLA) indicate that osseous integration is improved and that these implants can be successfully restored six weeks after implant placement. Thus, Straumann implants have been shown to be successful in the mandible and the maxilla, in anterior and posterior regions, and in various indications including single-tooth replacements, short- and long-span fixed partial dentures, fixed and removable dentures and overdenture cases. These clinical experiences in patients over long evaluation periods reveal that Straumann implants and the ITI® Dental Implant System can be used successfully and predictably in multiple indications.

Acknowledgements

I would like to acknowledge the committee members for their help in preparing this review. I thank Karen Lucas for her expert secretarial assistance and Karen Holt for editing. Lastly, I would like to acknowledge Bill Ryan, Carolyn Bitetti, Linda Jalbert, Jim Simpson and other Straumann employees who helped assimilate the tables of studies, and Danny Buser for use of figures.

References

Albrektsson, T., Hansson, H.-A. & Ivarsson, B. (1985) Interface analysis of titanium and zirconium bone implants. *Biomaterials* **6**: 97–101.

Albrektsson, T. & Hansson, H.-A. (1986) An ultrastructural characterization of the interface between bone and sputtered titanium or stainless steel. *Biomaterials* **7**: 201–205.

Astrand, P., Almfeldt, I., Brunell, G., Hamp, S.E., Hellem, S. & Karlsson U. (1996) Nonsubmerged implants in the treatment of the edentulous lower jaw. *Clinical Oral Implants Research* **7**: 337–344.

Babbush, C., Kent, J. & Misiek D. (1986) Titanium plasma sprayed (TPS) screw implants for the reconstruction of the edentulous mandible. *Journal of Oral and Maxillofacial Surgery* **44**: 274–282.

Becker, W., Becker, B.E., Israelson, H., Lucchini, J.P., Handelsman, M., Ammons, W. Rosenberg, E., Rose, L., Tucker, L.M. & Lekholm, U. (1997) One-step surgical placement of Brånemark implants: a prospective multicenter clinical study. *International Journal of Oral and Maxillofacial Implants* **12**: 454–462.

Behneke, A., Behneke, N., d'Hoedt, B. & Wagner, W. (1997) Hard and soft tissue reactions to ITI screw implants: 3-year longitudinal results of a prospective study. *International Journal of Oral and Maxillofacial Implants* **12(6)**: 749–757.

Berglundh, T., Lindhe, J., Johnson, K. & Ericsson, I. (1994) The topography of the vascular systems in the periodontal and peri-implant tissues in the dog. *Journal of Clinical Periodontology* **21**: 189–193.

Bernard, J.-P., Belser, U.C., Martinet, J.-P. & Borgis, S.A. (1995) Osseointegration of Brånemark fixtures using a single-step operating technique. *Clinical Oral Implants Research* **6**: 122–129.

Buser, D., Weber, H.P. & Lang, N.P. (1990a) Tissue integration of nonsubmerged implants. 1-year results of a prospective study with 100 ITI hollow-cylinder and hollow-screw implants. *Clinical Oral Implants Research* **1**: 33–40.

Buser, D., Warrer, K. & Karring, T. (1990b) Formation of a periodontal ligament around titanium implants. *Journal of Periodontology* **61**: 597–601.

Buser, D., Warrer, K., Karring, T. & Stich H. (1990c) Titanium implants with a true periodontal ligament: an alternative to osseointegrated implants? *International Journal of Oral and Maxillofacial Implants* **5**: 113–116.

Buser, D., Schenk, R.K., Steinmann, S., Fiorellini, J.P., Fox, C.H. & Stich, H. (1991a) Influence of surface characteristics on bone integration of titanium implants. A histomorphometric study in miniature pigs. *Journal of Biomedical Materials Research* **25**: 889–902.

Buser, D., Weber, H.-P., Brägger, U. & Balsiger, C. (1991b) Tissue integration of one-stage ITI implants: 3-year results of a longitudinal study with hollow-cylinder and hollow-screw implants. *International Journal of Oral and Maxillofacial Implants* **6**: 405–412.

Buser, D., Weber, H.P., Donath, K., Fiorellini, J.P., Paquette, D.W. & Williams, R.C. (1992a) Soft tissue reactions to nonsubmerged unloaded titanium implants in beagle dogs. *Journal of Periodontology* **63**: 226–236.

Buser, D., Sutter, F., Weber, H.P., Belser, U. & Schroeder, A. (1992b) The ITI Dental Implant System: basics, indications, clinical procedures and results. *Clark's Clinical Dentistry* **1**: 1–23.

Buser, D., Dula, K., Lang, N.P. & Nyman, S. (1996) Long-term stability of osseointegrated implants in bone regenerated with the membrane technique. *Clinical Oral Implants Research* **7**: 175–183.

Buser, D., Mericske-Stern, R., Bernard, J.P., Behneke, A., Behneke, N., Hirt, H.P., Belser, U.C. & Lang, N.P. (1997) Long-term evaluation of nonsubmerged ITI implants. *Clinical Oral Implants Research* **8**: 161–172.

Buser, D., Nydegger T., Hirt, H.P., Cochran D.L. & Nolte, L.P. (1998) Removal torque values of titanium implants in the maxilla of miniature pigs. *International Journal of Oral and Maxillofacial Implants* **13**: 611–619.

Buser, D., Merickske-Stern, R., Dula, K. & Lang, N.P. (1999) Clinical experience with one-stage, non-submerged dental implants. *Advances of Dental Research*, **13**: 153–161.

Carlsson, L.V., Rostlund, T., Albrektsson, B. & Albrektsson, T. (1988) Removal torques for polished and rough titanium implants. *International Journal of Oral and Maxillofacial Implants* **3**: 21–24.

Carmichael, R.P., McCulloch, C.A.G. & Zarb, G.A. (1991) Quantitative immunohistochemical analysis of keratins and desmoplakins in human gingiva and peri-implant mucosa. *Journal of Dental Research* **70 (5)**: 899–905.

Chiapasco, M., Gatti, C., Rossi, E., Haefliger, W. & Markwalder, T.H. (1997) Implant-retained mandibular overdentures with immediate loading: a retrospective multicenter study on 226 consecutive cases. *Clinical Oral Implants Research* **8**: 48–57.

Christensen, M.M., Joss, A. & Lang, N.P. (1997) Reproducibility of automated periodontal probing around teeth and osseointegrated oral implants. *Clinical Oral Implants Research* **8**: 455–464.

Cochran, D.L. (1996) Implant therapy I. *Annals of Periodontology* **1**: 707–790.

Cochran, D.L. (1999) Endosseous dental implant surfaces in human clinical trials. A comparison using meta-analysis. *Journal of Periodontology* **70**: 1523–1539.

Cochran, D.L. & Mahn, D. (1992) Dental implants and regeneration. Part I. Overview and biological considerations. *Clark's Clinical Dentistry* **59**: 1–7.

Cochran, D.L., Simpson, J., Weber, H.P. & Buser, D. (1994) Attachment and growth of periodontal cells on smooth and rough titanium. *International Journal of Oral and Maxillofacial Implants* **9**: 289–297.

Cochran, D.L., Nummikoski, P.V., Higginbottom, F.L., Hermann, J.S., Makins, S.R. & Buser, D. (1996) Evaluation of an endosseous titanium implant with a sandblasted and acid-etched surface in the canine mandible: radiographic results. *Clinical Oral Implants Research* **7**: 240–252.

Cochran, D.L., Hermann, J.S., Schenk, R.K., Higginbottom, F.L. & Buser, D. (1997) Biologic width around titanium implants. A histometric analysis of the implanto-gingival junction around unloaded and loaded nonsubmerged implants in the canine mandible. *Journal of Periodontology* **68**: 186–198.

Cochran, D.L., Schenk, R.K., Lussi, A., Higginbottom, F.L. & Buser, D. (1998) Bone response to unloaded and loaded titanium implants with a sandblasted and acid-etched surface. A histometric study in the canine mandible. *Journal of Biomedical Materials Research,* **40**: 1–11.

Cochran, D.L., Buser, D., ten Bruggenkate, T.M., Weingart, D., Taylor, T.M., Bernard, J.P., Peters, F. & Simpson, J.P. (2000) The use of shortened healing times on ITI® implants with a sandblasted and acid-etched (SLA) surface: early results from clinical trials. *Clinical Oral Implants Research* (submitted).

Collaert, B. & De Bruyn H. (1998) Comparison of Brånemark fixture integration and short-term survival using one-stage or two-stage surgery in completely and partially edentulous mandibles. *Clinical Oral Implants Research* **9**: 131–135.

Cook, S., Kay, J., Thomas, K. & Jarcho M. (1987) Interface mechanics and histology of titanium and hydroxylapatite-coated titanium for dental implant applications. *International Journal of Oral and Maxillofacial Implants* **2**: 15–22.

Cook, S., Baffes, G., Palafox, A., Wolfe, M. & Burgess A. (1992) Torsional stability of HA-coated and grit-blasted titanium dental implants. *Journal of Oral Implantology* **18**: 354–358.

Cox, J.F. & Zarb, G.A. (1987) The longitudinal clinical efficacy of osseointegrated dental implants: a 3-year report. *International Journal of Oral and Maxillofacial Implants* **2**: 91–100.

Donatsky, O. & Hillerup, S. (1996) Nonsubmerged osseointegrated dental implants with ball attachments supporting overdentures in patients with mandibular alveolar ridge atrophy. *Clinical Oral Implants Research* **7**: 170–174.

Ellegaard, B., Baelum, V. & Karring, T. (1997) Implant therapy in periodontally compromised patients. *Clinical Oral Implants Research* **8**: 180–188.

Ericsson, I., Johansson, C.B., Bystedty, H. & Norton, M.R. (1994a) A histomorphometric evaluation of bone-to-bone implant contact on machine-prepared and roughened titanium dental implants: a pilot study in the dog. *Clinical Oral Implants Research* **5**: 202–206.

Ericsson, I., Randow, K., Glantz, P.O., Lindhe, J. & Nilner, K. (1994b) Clinical and radiographical features of submerged and nonsubmerged titanium implants. *Clinical Oral Implants Research* **5**: 185–189.

Ericsson, I., Nilner, K., Klinge, B. & Glantz, P.O. (1996) Radiographical and histological characteristics of submerged and nonsubmerged titanium implants. *Clinical Oral Implants Research* **7**: 20–26.

Ericsson, I., Randow, K., Nilner, K. & Petersson, A. (1997) Some clinical and radiographical features of submerged and nonsubmerged titanium implants. A 5-year follow-up study. *Clinical Oral Implants Research* **8**: 422–426.

Fartash, B., Arvidson, K. & Ericsson I. (1990) Histology of

tissues surrounding single crystal sapphire endosseous dental implants. *Clinical Oral Implants Research* **1**: 13–21.
François, P., Vaudaux, P., Taborelli, M., Tonetti, M., Lew, D.P. & Descouts, P. (1997) Influence of surface treatments developed for oral implants on the physical and biological properties of titanium. (II) Adsorption, isotherms and biological activity of immobilized fibronectin. *Clinical Oral Implants Research* **8**: 217–225.
Gargiulo, A.W., Wentz, F.M. & Orban, B. (1961) Dimensions and relations of the dentogingival junction in humans. *Journal of Periodontology* **32**: 261–267.
Gotfredsen, K., Hjørting-Hansen, E. & Budtz-Jørgensen E. (1990) Clinical and radiographical evaluation of submerged and nonsubmerged implants in monkeys. *International Journal of Prosthodontics* **3**: 463–469.
Gotfredsen, K., Rostrup, E., Hjørting-Hansen, E., Stoltze, K. & Budtz-Jørgensen, E. (1991) Histological and histomorphometrical evaluation of tissue reactions adjacent to endosteal implants in monkeys. *Clinical Oral Implants Research* **2**: 30–37.
Gotfredsen, K., Nimb, L., Hjørting-Hansen, E., Jensen, J.S. & Holmen, A. (1992) Histomorphometric and removal torque analysis for TiO_2-blasted titanium implants. An experimental study on dogs. *Clinical Oral Implants Research* **3**: 77–84.
Gould, T., Westbury, L. & Brunette, D. (1984) Ultrastructural study of the attachment of human gingiva to titanium *in vivo*. *Journal of Prosthetic Dentistry* **52**: 418–420.
Gratz, K.W., Zimmermann, A.P. & Sailer, H.F. (1994) Histological evidence of osseointegration 4 years after implantation. A case report. *Clinical Oral Implants Research* **5**: 173–176.
Hämmerle, H.F., Brägger, U., Bürgin, W. & Lang, N.P. (1996) The effect of subcrestal placement of the polished surface of ITI implants on marginal soft and hard tissues. *Clinical Oral Implants Research* **7**: 111–119.
Hermann, J.S., Cochran, D.L., Nummikoski, P.V. & Buser, D. (1997) Crestal bone changes around titanium implants. A radiographic evaluation of unloaded nonsubmerged and submerged implants in the canine mandible. *Journal of Periodontology* **68**: 1117–1130.
Hermann, J.S., Buser, D., Schenk, R.K. & Cochran, D.L. (2000) Crestal bone changes around titanium implants. A histometric evalution of unloaded nonsubmerged and submerged implants in the canine mandible. *Journal of Periodontology* (submitted).
James, R.A. & Schultz, R.L. (1974) Hemidesmosomes and the adhesion of junctional epithelial cells to metal implants. A preliminary report. *Oral Implantology* **4:** 294–302.
Jansen, J.A., de Wijn, J.R., Wolters-Lustgerhorst, J.M.L. & van Mullem, P.J. (1985) Ultrastructural study of epithelial cell attachment to implant materials. *Journal of Dental Research* **64**: 891–896.
Johansson, C. & Albrektsson, T. (1987) Integration of screw implants in the rabbit: a 1-year follow-up of removal torque of titanium implants. *International Journal of Oral and Maxillofacial Implants* **2**: 69–75.
Kieswetter, K., Schwartz, Z., Hummert, T.W., Cochran, D.L., Simpson, J., Dean, D.D. & Boyan, B.D. (1996) Surface roughness modulates the local production of growth factors and cytokines by osteoblast-like MG-63 cells. *Journal of Biomedical Materials Research* **32**: 55–63.
Krekeler, G., Schilli, W. & Diemer J. (1985) Should the exit of the artificial abutment tooth be positioned in the region of the attached gingiva? *International Journal of Oral Surgery* **14**: 504–508.
Krekeler, G., Schilli, W. & Geiger, H. (1990) Das TPS-Implantat, ein zuverlaessiges Retentionselement? *Zeitung für Zahnärztliche Implantologie*: 229–234.
Lang, N.P., Wetzel, A., Stich, H. & Caffesse, R. (1994) Histologic probe penetration in healthy and inflamed peri-implant tissues. *Clinical Oral Implants Research* **5**: 191–201.
Ledermann, P.D. (1984) Das TPS-Schraubenimplantat nach siebenjahriger Anwendung. *Chirurgische Zahnheilkunde* **11:** 1–11.
Lekholm, U., Adell, R. & Lindhe, J. (1986) Marginal tissue reactions at osseointegrated titanium fixtures. (II) A cross-sectional retrospective study. *International Journal of Oral and Maxillofacial Surgery* **15**: 53–61.
Levine, R.A., Clem, D.S., Wilson, T.G., Higginbotton, F. & Saunders, S.L. (1997) A multicenter retrospective analysis of the ITI implant system used for single-tooth replacements: preliminary results at 6 or more months of loading. *International Journal of Oral and Maxillofacial Implants* **12**: 237–242.
Levy, D., Deporter, D.A., Pilliar, R.M., Watson, P.A. & Valiquette, N. (1996) Initial healing in the beagle dog of submerged versus nonsubmerged porous-coated endosseous dental implants. *Clinical Oral Implants Research* **7**: 101–110.
Listgarten, M.A. (1992) Light and transmission electron microscopy of the intact interfaces between nonsubmerged titanium-coated epoxy resin implants and bone or gingiva. *Journal of Dental Research* **71**: 364–371.
Listgarten, M.A. (1996) Soft and hard tissue response to endosseous dental implants. *Anatomical Record (New York, NY)* **243**: 410–425.
Listgarten, M.A. & Lai, C. (1975) Ultrastructure of intact interface between an endosseous epoxy-resin dental implant and host tissues. *Journal Biologie Buccale* **3(1)**: 13–28.
Listgarten, M.A., Lang, N.P., Schroeder, H.E. & Schroeder, A. (1991) Periodontal tissues and their counterparts around endosseous implants. *Clinical Oral Implants Research* **2**: 1–19.
Martin, J.Y., Schwartz, Z., Hemmert, T.W., Schraub, D.M., Simpson, J., Lankford, J., Dean, D.D., Cochran, D.L. & Boyan, B.D. (1995) Effect of titanium surface roughness on proliferation, differentiation, and protein synthesis of human osteoblast-like cells. *Journal of Biomedical Materials Research* **29**: 389–401.
McKinney, R., Steflik, D. & Koth D. (1985) Evidence for a junctional epithelial attachment to ceramic dental implants. A transmission electron microscopic study. *Journal of Periodontology* **56**: 579–591.
McKinney, R., Steflik, D. & Koth, D. (1988) The epithelium dental implant interface. *Journal of Oral Implantology* **8**: 622–637.
Meffert, R., Langer, B. & Fritz, M. (1992) Dental implants: a review. *Journal of Periodontology* **63**: 859–870.
Mericske-Stern, R. (1990) Clinical evaluation of overdenture restorations supported by osseointegrated titanium implants: a retrospective study. *International Journal of Oral and Maxillofacial Implants* **5**: 375–383.
Mericske-Stern, R., Schaffner, T.S., Marti, P. & Geering, A.H. (1994) Peri-implant mucosal aspects of ITI implants supporting overdentures: a five-year longitudinal study. *Clinical Oral Implants Research* **5**: 9–18.
Mericske-Stern, R., Milani, D., Mericske, E. & Olah, A. (1995) PerioTest measurements and osseointegration of mandibular ITI implants supporting overdentures. *Clinical Oral Implants Research* **6**: 73–82.
Mombelli, A., Mühle, T., Brägger, U., Lang, N.P. & Bürgin, W.B. (1997) Comparison of periodontal and peri-implant probing by depth-force pattern analysis. *Clinical Oral Implants Research* **8**: 448–454.
Naert, I., De Clercq, M., Thuniers, G. & Schepers E. (1988) Overdentures supported by osseointegrated fixtures for the edentulous mandible: a 2.5 year report. *International Journal of Oral and Maxillofacial Implants* **3**: 191–196.
Nishimura, K., Itoh, T., Takaki, K., Hosokawa, R., Naito, T. &

Yokota, M. (1997) Periodontal parameters of osseointegrated dental implants. *Clinical Oral Implants Research* **8**: 272–278.

Persson, L.G., Lekholm, U., Leonhardt, A., Dahlén, G. & Lindhe, J. (1996) Bacterial colonization on internal surfaces of Brånemark system® implant components. *Clinical Oral Implants Research* **7**: 90-95.

Pham, A.N., Fiorellini, J.P., Paquette, D., Williams, R.C. & Weber, H.C. (1994) Longitudinal radiographic study of crestal bone levels adjacent to nonsubmerged dental implants. *Journal of Oral Implantology* **20**: 26–34.

Piattelli, A., Ruggeri, A., Franchi, M., Romasco, N. & Trisi, P. (1993) An histologic and histomorphometric study of bone reactions to unloaded and loaded nonsubmerged single implants in monkeys: a pilot study. *Journal of Oral Implantology* **19**: 314–319.

Piattelli, A., Scarano, A., Piatelli, M., Bertolai, R. & Panzoni, E. (1997) Histologic aspects of the bone and soft tissues surrounding three titanium nonsubmerged plasma-sprayed implants retrieved at autopsy: a case report. *Journal of Periodontology* **68**: 694–700.

Quirynen, M. & van Steenberghe, D. (1993) Bacterial colonization of the internal part of two-stage implants. An *in vivo* study. *Clinical Oral Implants Research* **4**: 158–161.

Romanos, G., Schroter-Kermani, C., Weingart, D. & Strub J. (1995) Healthy human periodontal versus peri-implant gingival tissues: an immunohistochemical differentiation of the extracellular matrix. *International Journal of Oral and Maxillofacial Implants* **10**: 750–758.

Ruggeri, A., Franchi, M., Marini, N., Trisi, P. & Piattelli A. (1992) Supracrestal circular collagen fiber network around osseointegrated nonsubmerged titanium implants. *Clinical Oral Implants Research* **3**: 169–175.

Ruggeri, A., Franchi, M., Trisi, P. & Piattelli A. (1994) Histologic and ultrastructural findings of gingival circular ligament surrounding osseointegrated nonsubmerged loaded titanium implants. *International Journal of Oral and Maxillofacial Implants* **9**: 636–643.

Sandberg, E., Dahlin, C. & Linde, A. (1993) Bone regeneration by the osteopromotion technique using bioabsorbable membranes. An experimental study in rats. *Journal of Oral and Maxillofacial Surgery* **51**: 1106–1114.

Schmid, J., Cohen, R.L. & Chambers, D.A. (1991) Plasminogen activator in human periodontal health and disease. *Archives of Oral Biology* **36**: 245–250.

Schmid, B., Spicher, I., Schmid, J. & Lang, N.P. (1992) Plasminogen activator in human gingival tissue adjacent to dental implants. *Clinical Oral Implants Research* **3**: 85–89.

Schroeder, H.E. (1969) Ultrastructure of the junctional epithelium of the human gingiva. *Helvetica Odontologie Acta* **13**: 65–82.

Schroeder, H.E. & Listgarten, M.A. (1971) *Fine structure of the developing epithelial attachment of human teeth*. Basel, München, Paris, London, New York, Sydney: Monographs in Developmental Biology, 2: 1–134.

Schroeder, A., Pholer, O. & Sutter, F. (1976) Gewebsreaktion auf ein titan-hohlzylinderimplantat mit titan-spritzschichtoberfläche. *Schweizerische Monatsschrift für Zahnheilkunde* **86**: 713–727.

Schroeder, A., Stich, H., Straumann, F. & Sutter, F. (1978) Über die anlagerung von osteozement an einen belasteten implantatkörper. *Schweizerische Monatsschrift für Zahnheilkunde* **88**: 1051–1058.

Schroeder, A., Zypen, E., Stich, H. & Sutter, F. (1981) The reactions of bone, connective tissue, and epithelium to endosteal implants with titanium-sprayed surfaces. *Journal of Maxillofacial Surgery* **9**: 15–25.

Schwartz, Z., Martin, J.Y., Dean, D.D., Simpson, J., Cochran, D.L. & Boyan, B.D. (1996) Effect of titanium surface roughness on chondrocyte proliferation, matrix production, and differentiation depends on the state of cell maturation. *Journal of Biomedical Materials Research* **30**: 145–155.

Seymour, G.J., Gemmell, E., Lenz, L.J., Henry, P., Bower, R. & Yamazaki, K. (1989) Immunohistologic analysis of the inflammatory infiltrates associated with osseointegrated implants. *International Journal of Oral and Maxillofacial Implants* **4**: 191–198.

Spiekermann, H., Jansen, V. & Richter, E.-J. (1995) A 10-year follow-up study of IMZ and TPS implants in the edentulous mandible using bar-retained overdentures. *International Journal of Oral Maxillofacial Implants* **10**: 231–243.

Steflik, D. & McKinney R. (1989) Ultrasound comparisons of ceramic and titanium dental implants *in vivo*: a scanning electron microscopic study. *Journal of Biomedical Materials Research* **23**: 895–909.

Steflik, D., Sisk, A., Parr, G., Lake, F. & Hanes, P. (1993) Experimental studies of the implant-tissue interface. *Journal of Oral Implantology* **19**: 90-94.

Steinemann, S.G., Eulenberger, J., Mausli, P. & Schroeder, A. (1986) Adhesion of bone to titanium. *Biological and Biomechanical Performance of Biomaterials* **6**: 404–414.

Taborelli, M., Jobin, M., François, P., Vaudaux, P., Tonetti, M., Szmukler-Moncler, S., Simpson, J.P. & Descouts, P. (1997) Influence of surface treatments developed for oral implants on the physical and biological properties of titanium. (I) Surface characterization. *Clinical Oral Implants Research* **8**: 208–216.

Takeshita, F., Suetsugu, T., Higuchi, Y. & Oishi, M. (1996) Histologic study of failed hollow implants. *International Journal of Oral and Maxillofacial Implants* **11**: 245–250.

Takeshita, F., Iyama, S., Ayukawa, Y., Suetsugu, T. & Oishi M. (1997) Failing hollow implants examined by light microscopy and image processing. *Journal of Periodontology* **68**: 293–298.

Tarnow, D.P., Emtiaz, S. & Classi A. (1997) Immediate loading of threaded implants at stage 1 surgery in edentulous arches: ten consecutive case reports with 1- to 5-year data. *International Journal of Oral and Maxillofacial Implants* **12**: 319–324.

ten Bruggenkate, C.M., van der Kwast, W.A. & Oosterbeek, H.S. (1991) Patient selection in oral implantology – a review. *International Journal of Oral Implantology* **7**: 53–60.

Thomas, K. & Cook, S. (1985) An evaluation of variables influencing implant fixation by direct bone apposition. *Journal of Biomedical Materials Research* **19**: 875–901.

Thomas, K., Kay, J., Cook, S. & Jarcho, M. (1987) The effect of surface macrotexture and hydroxylapatite coating on the mechanical strengths and histologic profiles of titanium implant materials. *Journal of Biomedical Materials Research* **21**: 1395–1414.

Tonetti, M.S., Schmid, J., Hämmerle, C.H.F. & Lang, N.P. (1993) Intraepithelial antigen-presenting cells in the keratinized mucosa around teeth and osseointegrated implants. *Clinical Oral Implants Research* **4**: 177–186.

Tonetti, M.S. & Schmid, J. (1994) Pathogenesis of implant failures. In: Lang, N.P. & Nyman, S., eds. *Periodontology 2000: Implant and crown and bridge therapy in the periodontally compromised patient*, 127–138.

Van Beek, G.J. & van Gool, A.V. (1991) The indications and results of the ITI implant and the TMI. *Oral Surgery Oral Diagnosis* **2:** 11–17.

Van Gool, A., Vermeeren, J.I.J.F., ten Bruggenkate, C.M. & van Beek, G.J. (1992) ITI Impantaten in Nederland. Evaluatie von 2,454 Implantaten. *Nederlands Tijdschrift voor Tandheelkunde* **99:** 461.

van Steenberghe, D., Klinge, B., Linden, U., Quirynen, M., Herrman, I. & Garpland C. (1993) Periodontal indices around natural and titanium abutments: a longitudinal multicenter study. *Journal of Periodontology* **64**: 538–541.

Warrer, K. & Karring, T. (1993) Periodontal ligament formation around different types of dental titanium implants. I. The self-tapping screw type implant system. *Journal of Periodontology* **64**: 29–34.

Weber, H.P., Buser, D., Donath, K., Fiorellini, J.P., Doppalapudi, V., Paquette, D.W. & Williams, R.C. (1996) Comparison of healed tissues adjacent to submerged and nonsubmerged unloaded titanium dental implants. *Clinical Oral Implants Research* **7**: 11–19.

Wennerberg, A., Albrektsson, T., Andersson, B. & Krol, J. (1995) A histomorphometric and removal torque study of screw-shaped titanium implants with three different surface topographies. *Clinical Oral Implants Research* **6**: 24–30.

Wilke, H.J., Claes, L. & Steinemann, S. (1990) The influence of various titanium surfaces on the interface shear strength between implants and bone. In: Heimke, G., Soltész, U. & Lee, A.J.C., eds. *Advances in Biomaterials – Clinical Implant Materials*, Vol. 9, 309–314. Amsterdam, New York, Oxford: Elsevier Science Publishers B.V.

Wismeyer, D., van Waas, M.A. & Vermeeren, J.I. (1995) Overdentures supported by ITI implants: a 6.5-year evaluation of patient satisfaction and prosthetic aftercare. *International Journal of Oral & Maxillofacial Implants* **10**: 744–749.

Wong, M., Eulenberger, J., Schenk, R. & Hunziker, E. (1995) Effect of surface topology on the osseointegration of implant materials in trabecular bone. *Journal of Biomedical Materials Research* **29**: 1567–1575.

Zarb, G.A. & Schmitt, A. (1990a) The longitudinal clinical effectiveness of osseointegrated dental implants: The Toronto study. Part I: Surgical results. *Journal of Prosthetic Dentistry* **63**: 451–457.

Zarb, G.A. & Schmitt, A. (1990b) The longitudinal clinical effectiveness of osseointegrated dental implants: The Toronto study. Part II: The prosthetic results. *Journal of Prosthetic Dentistry* **64**: 53–61.

Zarb, G.A. & Schmitt, A. (1990c) The longitudinal clinical effectiveness of osseointegrated dental implants: The Toronto study. Part III: Problems and complications encountered. *Journal of Prosthetic Dentistry* **64**: 185–194.