The Effects of Laser Microgrooves on Hard and Soft Tissue Attachment to Implant Collar Surfaces: A Literature Review and Interpretation

Mohammad Ketabi, DDS, MDS (Perio)[1]
Douglas Deporter, DDS, PhD[2]

This paper summarizes current knowledge on the benefits of laser-ablated microgrooves in neck regions of endosseous dental implants. Like machine-tooled coronal microthreads with particle-blasted surfaces, laser-ablated microgrooves help to preserve crestal bone. However, they also appear to uniquely favor a true gingival connective tissue attachment comparable to that of natural teeth. (Int J Periodontics Restorative Dent 2013;33:e145–e152. doi: 10.11607/prd.1629)

[1]Dean and Professor and Chairman, Department of Periodontology, Faculty of Dentistry, Islamic Azad University (Khorasgan Branch), Arghavanieh, Isfahan, Iran.
[2]Professor, Discipline of Periodontology, Oral Reconstructive Center, Faculty of Dentistry, University of Toronto, Toronto, Ontario, Canada.

Correspondence to: Dr Douglas Deporter, Faculty of Dentistry, University of Toronto, 124 Edward Street, Toronto, Ontario, Canada M5G 1G6; email: douglas.deporter@utoronto.ca.

Peri-implant gingiva such as that of teeth should provide a protective barrier against microbial plaque. Recent work has indicated a need for keratinized gingiva of adequate width and thickness to reduce peri-implant soft tissue recession and bone loss.[1–3] Gingival tissues surrounding the necks of teeth and implants have similarities, with both consisting of a stratified squamous keratinized epithelium secured by hemi-desmosomes overlying a dense, collagenous lamina propria.[4–6] These soft tissue components must be of minimum thickness or "biologic width" to avoid an accommodating degree of crestal bone loss.[7–9] The difference around implants compared with teeth is that with the latter, collagen fibers insert directly into cementum as Sharpey fibers, more or less perpendicular to root surfaces.[10] In contrast, collagen fibers of peri-implant lamina propria present as a fibrous capsule with fibers oriented parallel and circumferential to the implant surface.[11]

Collar segments (eg, the portion of the implant root immediately apical to the microgap of two-piece implants) traditionally

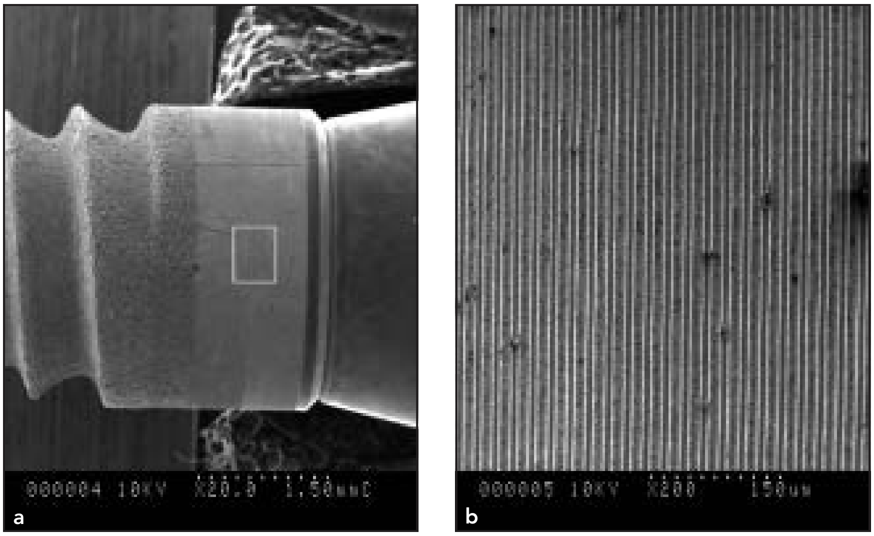


Fig 1a *Low-power image of an implant with laser-etched microgrooves on its collar segment. A higher-power magnification of the area marked with the rectangle is shown in Fig 1b.*

Fig 1b *Laser-etched microgrooves (original magnification ×200).*

had machine-turned surfaces to accommodate "biologic width." However, recently, manufacturers have moved toward providing moderate surface roughness on implant collars, and this approach has had variable outcomes. One promising collar surface treatment has been the creation of microgrooves by laser ablation. This design feature appears to promote a more tooth-like gingival collagen fiber attachment.[12] The aim of this paper was to review existing literature supporting the use of laser microgrooves on implant collars.

Method and materials

A literature search of publications in refereed journals in the English language from 1990 to July 2011 was performed using the National Library of Medicine and SCOPUS Cochrane Oral Health Group databases. Additional papers from reference lists of identified papers, but preceding 1990, were also reviewed. Relevant references were selected on the basis of titles and abstracts, but final selections were based on full-text review independently by the two authors. The search strategy included a specific series of terms and key words including: biologic width, crestal bone, implant collar, tissue engineering, surface topography, connective tissue contact, laser ablation, microgrooves, and dental implants, with different key words connected with "OR" and "AND." Relevant publications included in vitro experiments, finite element analyses, animal studies, and human clinical, radiographic, and histologic studies.

Results

Laser treatment can be used to create precise circumferential microgrooves in neck segments of dental implants as a result of localized heating resulting in metal vaporization, localized melting, and rapid resolidification (Figs 1a and 1b). This type of microgeometry has been shown to have directional effects on fibroblasts both in vitro and in vivo. Ricci et al[13] reported that cultured fibroblasts grown on microgrooved polystyrene surfaces vapor-deposited with titanium oxide became oriented or channeled ("contact guidance") in line with the grooves. In comparison, cells grown on nongrooved surfaces showed random growth. Groove widths of 6 to 12 μm appeared to work best.[14] Dumas et al[15] reported that laser-ablated microgrooves created on titanium alloy (Ti-6Al-4V) also had 600-nm nanostructures promoting oriented cell filipodial contact and fibrin fibril orientation in vitro. This moderate level of surface roughness (Fig 2) is not unlike that seen with other surface treatments such as acid etching.[16,17]

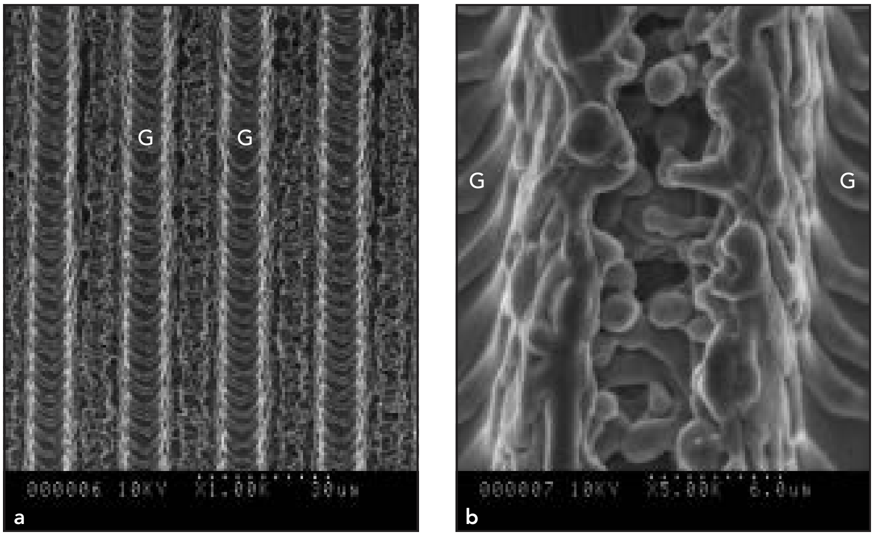


Fig 2a *Laser-etched microgrooves* (G) *(original magnification ×1,000).*

Fig 2b *Laser-etched microgrooves (original magnification ×5,000). A ladder-like smooth-edged nanostructure can be seen in the grooves* (G) *themselves, while the intergroove ridges have a knobby appearance indicative of melting and resolidification with smooth edges and some undercuts.*

Animal studies with laser-treated implants

Weiner et al[18] used dogs to examine the responses of bone, connective tissue, and epithelium to laser microtextured collars on particle-blasted, threaded implants. Collar length was 2 mm prepared with three distinct zones. The deepest 0.8-mm zone had laser-ablated microgrooves of 12 μm width and 10 ± 3 μm depth. A middle 0.7-mm zone width had microgrooves of 8 μm width and 4 ± 1 μm depth, while the uppermost 0.5-mm zone was machine-turned. Control implants had fully machine-turned collars. Histometric data were prepared for loaded and unloaded implants after 3 or 6 months. At 3 months, unloaded test implants showed bone or soft tissue on the microgrooves depending on the characteristics of contacting tissue. Machined-collar surfaces of unloaded control implants showed only soft tissue contact. For loaded test implants, the machine-turned 0.5 mm of collar showed primarily epithelial contact, while laser microgrooves showed soft connective tissue attachment coronally and bone more apically. Machine-turned collars of loaded control implants showed mostly soft tissue contact and some crestal bone saucerization.

Nevins et al[19] used dogs to study healing with 8-μm-wide laser-ablated microgrooves on implant abutments rather than on implant collars. All implants were threaded with particle-blasted surfaces, and four implant/abutment combinations were studied. Group A consisted of fully particle-blasted implants, ie, without a machine-turned collar (MTC). Their abutments had an apical (ie, immediately coronal to implant-abutment microgap) 0.7-mm-wide zone of laser microgrooves. Group B implants had a 0.3-mm-wide MTC and abutments identical to group A. Group C implants had fully particle-blasted surfaces and fully machine-turned abutments, while group D had a 0.3-mm MTC and fully machine-turned abutments. All abutments were installed at the time of implant placement. Specimens were retrieved en bloc after 3 months. Histologic, high-resolution micro-computed tomography (micro-CT) and scanning electron microscope (SEM) observations of groups A and B demonstrated connective tissue fiber attachment oriented perpendicular to the abutment microgrooves. Apical migration of junctional epithelium (JE) was inhibited, and crestal bone loss was prevented by the laser-treated zone. In group A, bone growth into the microgap and onto the microgrooves was seen in some specimens. A more or less similar outcome was seen in group B. In group C, the formation of a long JE along the abutment and particle-blasted collar prevented oriented connective tissue attachment. A similar outcome was seen in group D with the addition of some crestal bone loss adjacent to the MTC.

Kim et al[20] used dogs to study early tissue responses for three different one-piece implant systems having different profiles and surface features on transmucosal segments. One group of implants (FM) had a flared, machine-turned, transmucosal segment (TMS). A second group (CMG) had a concave TMS shape and machine-turned surface, but with the addition of machine-tooled microgrooves of 30-μm width in the most apical zone. The third group (SA) had a straight TMS with an anodic oxidized surface (Ti-Unite, NobelDirect implant, Nobel Biocare). A total of 30 implants (10 of each type) were placed randomly in dog mandibles Specimens were retrieved en bloc after 6 months of nonfunctional, nonsubmerged healing. Histometric analysis showed that the CMG design was superior to the other designs since the machine-tooled, microgrooved zone allowed the greatest connective tissue contact (CTC) with less bone resorption. Whether CTC was oriented parallel or oblique to the microgrooves was not specified, but it is unlikely that oriented fiber attachment occurred since this has never been reported for machined implant surfaces.[8]

Human studies

Several investigators have reported clinical performance of dental implants with laser microgrooves on their collar segments. Nevins et al[12] did a histologic proof-of-principle study with Laser-Lok implants (Biohorizons). Implants had collars with three distinct surface treatments. The most apical 0.8 mm of collar had laser microgrooves of 12 μm width and 12 μm depth. An intermediate 0.7-mm zone had microgrooves of 8 μm width, 6 μm depth, while the coronal-most 0.5-mm zone was machine-turned. Four implants were retrieved en bloc from four patients after 6 months nonsubmerged healing. Prepared specimens were examined by light microscopy including polarized light, micro-CT, and SEM. Results showed the laser microgrooves to be covered with functionally oriented collagen fibers with prevention of apical epithelial migration and no crestal bone loss. This was in contrast to machined abutment surfaces where oriented collagen fibers did not extend to or attach to the metal surface, being separated from it by a 200-μm-thick layer of parallel oriented fibers.[21]

Nevins et al[22] later presented polarized light histologic data from two patients to support their canine data showing an oriented gingival fiber attachment to healing abutments with laser microgrooves. Geurs et al[23] reported a similar outcome with laser-treated healing abutments examined by polarized light and SEM microscopy. Finally, Nevins et al[24] presented polarized light histologic evidence from one patient that oriented gingival fibers that had developed in relation to laser-ablated microgrooves on a healing abutment can reattach to microgrooves on definitive prosthetic abutments. This reattachment of gingival fibers to the prosthetic abutment was apparently achieved without crestal bone loss.

Pecora et al[25] provided prospective, controlled data for a group of 15 patients and 20 pairs of Laser-Lok (LL) and control implants. Both implant models were tapered, threaded, and particle-blasted. Test implants had 2-mm collars on which the most apical 0.8 mm had laser microgrooves (12 μm width, 10 μm depth). An intermediate 0.7-mm zone had laser microgrooves of 8 μm width and 5 μm depth, and a coronal 0.5-mm zone was machine-turned. Control implants had fully machine-turned collars. During 37 months of clinical monitoring, LL implants showed significantly less pocket probing depth than controls, while at 7 months and later, they also showed less crestal bone loss (0.59 mm vs 1.94 mm). Similar results were presented by Botos et al,[26] who used Laser-Lok as test and Nobel Select (Nobel Biocare) as control implants, the latter having fully machined collars. Fifteen edentulous patients each received two of each implant type in the anterior mandible. One of each type was loaded immediately by supporting ball-retained overdentures, while the remaining two implants in each patient acted as nonloaded controls. Pocket probing depths and crestal bone loss for loaded LL implants were both significantly less than with controls at 6 and 12 months (eg, 0.72 mm vs 1.13 mm bone loss at 12 months). Bone loss was also less for nonloaded LL implants.

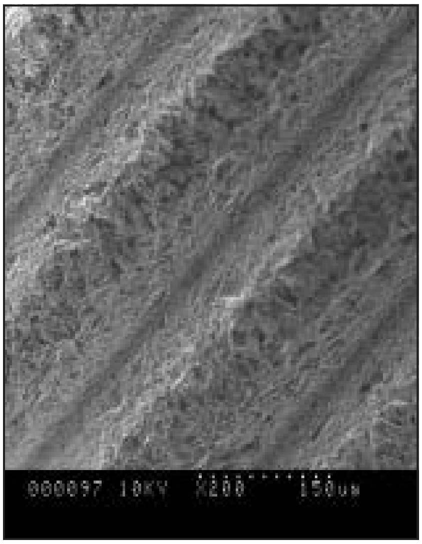


Fig 3a *Titanium oxide–blasted implant in the microthreaded collar region (original magnification ×200).*

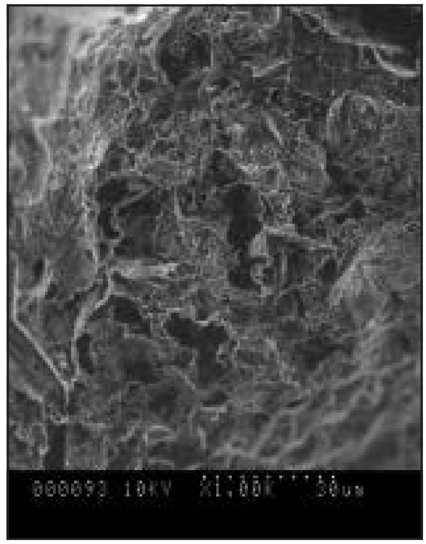


Fig 3b *A higher-power (original magnification ×1,000) image of the blasted surface in the microthreaded region.*

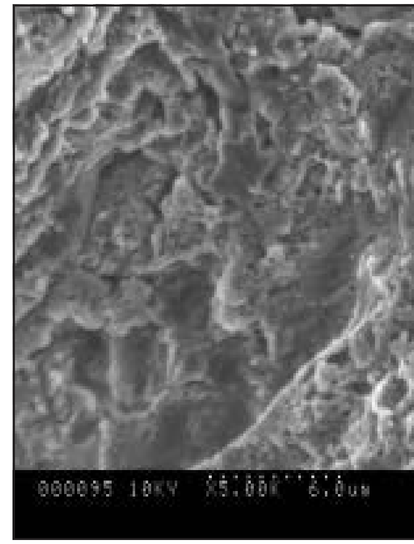
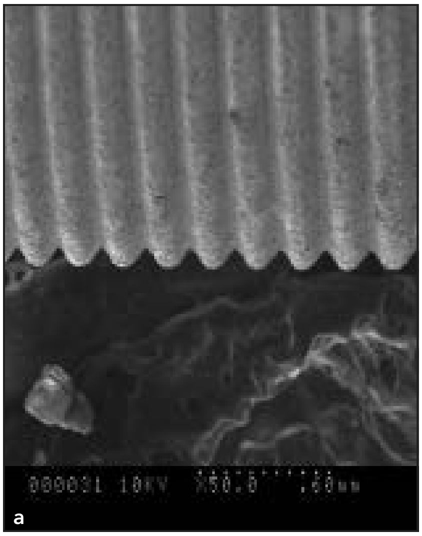


Fig 3c *The same sample as in Fig 3b, but magnified at ×5,000.*

The radiographic data for bone loss with LL implants presented by Pecora et al[25] and Botos et al[26] were similar to earlier noncontrolled retrospective data for 49 LL implants.[27] After 2 and 3 years in function, crestal bone loss values were 0.44 mm and 0.46 mm, respectively, and all bone loss was contained to the machined collars. These outcomes support findings from finite element analyses comparing stresses predicted following axial and side loading of implants having laser-treated versus machine-turned collars.[28] Laser-treated collars were predicted to exhibit significantly lower peak stresses on crestal bone (22.6 MPa for laser vs 91.9 MPa for machine-turned).

Discussion

Endosseous dental implants initially had machine-turned collar surfaces, and this typically led to crestal bone dieback to the level of the first implant thread.[29–31] However, short threaded implants may have greater crestal bone loss than longer ones, and bone loss is almost always greater in smokers than nonsmokers.[32] Investigators have further shown that coronal machine-tooled microthreads[33,34] and/or platform switching[35,36] can reduce crestal bone loss significantly, in both cases likely due to changes in bone stresses.[37,38] Implants with crestal machine-tooled microthreads also have moderately rough surfaces over their entire lengths, including the microthreaded segment (Fig 3), but retention of crestal bone is not likely due to this roughness. Lee et al[33] performed a human study comparing implants with and without microthreads, both having particle-blasted surfaces. Those without microthreads showed significantly greater bone loss. Likewise, comparison of implants with moderately rough-surfaced microthreads with implants having the Ti-Unite surface (thickened surface oxide layer), another moderately rough surface texture, but without microthreads showed the latter to suffer significantly greater bone loss at 1 year (0.81 mm vs 0.42 mm).[39] As well,



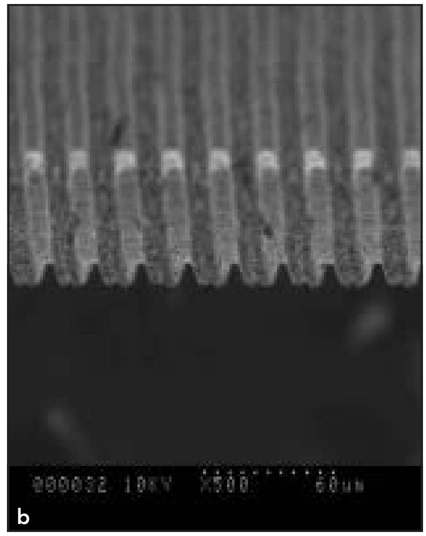


Fig 4a *This SEM image shows the particle-blasted microthreaded region of an Astra Tech implant at ×50 magnification.*

Fig 4b *This SEM image shows laser-ablated microgrooves (original magnification ×500). Comparing this image to Fig 4a, one can appreciate the difference in dimensions (an order of magnitude smaller) compared to microtooled, particle-blasted microthreads.*

implants without coronal microthreads but with the same surface roughness (particle-blasted) on their nonthreaded collar segment resulted in crestal bone loss similar to that seen with traditional fully machine-turned collars.[40,41] All of these observations could be interpreted to mean that a microthreaded geometry is more important in retaining crestal bone than moderate surface roughness. However, comparison between implant designs with coronal microthreads, but one design with and one without a moderately rough collar surface, has not to the authors' knowledge been done. Nevertheless, manufacturers have moved to producing implants without coronal microthreads but with moderately rough surfaces in their neck regions, and clinical performance has not always been good. Aalam and Nowzari[31] reported greater crestal bone loss with Ti-Unite surfaced implants than with fully machine-turned implants, although the differences were not significant.

However, the NobelDirect implant (Nobel Biocare), a one-piece implant with a Ti-Unite surface and without microthreads, showed unacceptably high failure rates due to progressive bone loss.[42] On the other hand, fully acid-etched two-piece implants with more or less the same surface roughness as Ti-Unite[43] and again without microthreads had no negative impact on crestal bone compared to the same implants without acid-etched surfaces on their collars and first three threads. Nevertheless, unlike laser-ablated surfaces, particle-blasted and/or acid-washed or Ti-Unite surfaces do not elicit functionally oriented gingival attachment to their roughened necks regardless of whether they have microthreads.[19,45–49] This is an interesting observation that may relate to the fact that laser microgrooves are an order of magnitude smaller in dimension than machine-tooled microthreads (Fig 4). As well, surface nanotopographies differ substantially (compare for example the images in Figs 2c and 3c). The nanotopography of laser-ablated surfaces is more pronounced, having knobs with rounded edges and some undercuts. In contrast, blasted surfaces on machine-tooled microthreads show random nanoroughness and somewhat sharp edges. Nano features have been shown by others to influence fibroblast behavior and strength of adhesion through filopodial sensing,[15,50,51] and one might speculate that nanosize surface features created by laser have the ability to allow fibroblasts to form a true connective tissue attachment to titanium implants.

Conclusions

Dental implants with laser-ablated coronal microgrooves or particle-blasted machine-tooled microthreads reduce peri-implant crestal bone loss compared to implants with fully machine-turned or particle-blasted (without the addition of microthreads) collar segments. However, unlike machine-tooled microthreads, laser microgrooves appear to inhibit apical migration of crevicular epithelium and promote true attachment of peri-implant gingiva. Since both treatments result in similar surface roughness, the difference in response of connective tissue may relate to differences in nanotopography and the fact that laser microgrooves are an order of magnitude smaller in dimension than machine-tooled microthreads.

It can be speculated that formation of a connective tissue–implant collar interface more like that of a natural tooth will improve long-term performance of dental implants. However, randomized, controlled, prospective trials comparing implants with laser-treated collars to those with moderately rough coronal microthreads, including accurate measurements of crestal bone loss over at least 5 years of clinical service, are required to investigate this hypothesis.

Acknowledgments

The authors wish to thank Professor Emeritus Robert Pilliar, University of Toronto, for his helpful comments and for providing the SEM images. Mrs Janissa Wan kindly assisted with the final preparation and submission of the manuscript. The authors reported no conflicts of interest related to this study.

References

1. Block M, Gardiner D, Kent J, Misiek D, Finger I, Guerra L. Hydroxyapatite-coated cylindrical implants in the posterior mandible: 10-year observations. Int J Oral Maxillofac Implants 1996;11:626–633.
2. Bouri A, Bissada N, Al-Zahrani MS, Faddoul F, Nouneh I. Width of keratinized gingiva and the health status of the supporting tissues around dental implants. Int J Oral Maxillofac Implants 2008;23:323–326.
3. Linkevicius T, Apse P, Grybauskas S, Puisys A. The influence of soft tissue thickness on crestal bone changes around implants: A 1-year prospective controlled clinical trial. Int J Oral Maxillofac Implants 2009;24:712–719.
4. Berglundh T, Lindhe J., Ericsson I, Marinello C, Liljenberg B, Thomsen P. The soft tissue barrier at implants and teeth. Clin Oral Implants Res 1991;2:81–90.
5. Listgarten M, Lang N, Schroeder H, Schroeder A. Periodontal tissues and their counterparts around endosseous implants. Clin Oral Implants Res 1991;2:1–19.
6. Buser D, Weber H, Donath K, Fiorellini J, Paquette D, Williams R. Soft tissue reactions to non-submerged unloaded titanium implants in beagle dogs. J Periodontol 1992;63:225–235.
7. Gargiulo A, Wentz F, Orban B. Dimensions and relations of the dentogingival junction in humans. J Periodontol 1961;32:261–267.
8. Abrahamsson I, Berglundh T, Wennstrom J, Lindhe J. The peri-implant hard and soft tissues at different implant systems: A comparative study in the dog. Clin Oral Implants Res 1996;7:212–219.
9. Berglundh T, Lindhe J. Dimension of the peri-implant mucosa. Biological width revisited. J Clin Periodontol 1996;23:971–973.
10. Ten Cate AR. Oral Histology. Development, Structure and Function. St Louis: Mosby, 1980.
11. Degidi M, Piatelli A, Scarano A, Shibli J, Iezzi G. Peri-implant collagen fibers around human cone morse connection implants under polarized light: A report of three cases. Int J Periodontics Restorative Dent 2012;32:323–328.
12. Nevins M, Nevins M, Camelo M, Boyesen J, Kim D. Human histologic evidence of a connective tissue attachment to a dental implant. Int J Periodontics Restorative Dent 2008;28:111–121.
13. Ricci J, Grew J, Alexander H. Connective-tissue responses to defined biomaterial surfaces. I. Growth of rat fibroblast and bone marrow cell colonies on microgrooved substrates. J Biomed Mater Res A 2008;85: 313–325.
14. Chehroudi B, Gould T, Brunette D. Titanium-coated micromachined grooves of different dimensions affect epithelial and connective-tissue cells differently in vivo. J Biomed Mater Res 1990;24:1203–1219.
15. Dumas V, Rattner A, Vico L, et al. Multiscale grooved titanium processed with femtosecond laser influences mesenchymal stem cell morphology, adhesion, and matrix organization. J Biomed Mater Res A 2012;100:3108–3116.
16. Albrektsson T, Wennerberg A. Oral implant surfaces: Part I: Review focusing on topographic and chemical properties of different surfaces and in vivo responses to them. Int J Prosthodont 2004;17:536–543.
17. Davies J. Mechanisms of endosseous integration. Int J Prosthodont 1998;11:391–401.
18. Weiner S, Simon J, Ehrenberg D, Zweig B, Ricci J. The effects of laser microtextured collars upon crestal bone levels of dental implants. Implant Dent 2008;17:217–228.
19. Nevins M, Kim M, Jun S, Guze K. Histologic evidence of connective tissue attachment to laser micro-grooved abutments: A canine study. Int J Periodontics Restorative Dent 2010;30:245–255.
20. Kim S, Oh K, Han D, et al. Influence of transmucosal designs of three one-piece implant systems on early tissue responses: A histometric study in beagle dogs. Int J Oral Maxillofac Implants 2010;25:309–314.

21. Degidi M, Piatelli A, Scarano A, Shibli J, Iezzi G. Peri-implant collagen fibers around morse connection implants under polarized light: A report of three cases. Int J Periodontics Restorative Dent 2012;32:323–328.
22. Nevins M, Camelo M, Nevins ML, Schupbach P, Kim D. Connective tissue attachment to laser-micro-grooved abutments: A human histologic case report. Int J Periodontics Restorative Dent 2012;32: 385–392.
23. Geurs N, Vassilopoulos P, Reddy M. Histologic evidence of connective tissue integration on laser microgrooved abutments in humans. Clin Adv Periodontics 2011;1:29–33.
24. Nevins M, Camelo M, Nevins ML, Schupbach P, Kim D. Re-attachment of connective tissue fibers to a laser-microgrooved abutment surface. Int J Periodontics Restorative Dent 2012;32:e131–e134.
25. Pecora G, Ceccarelli R, Bonelli M, Alexander H, Ricci J. Clinical evaluation of laser micro-texturing for soft tissue and bone attachment to dental implants. Implant Dent 2009;18:57–66.
26. Botos S, Yousef H, Zweig B, Flinton R, Weiner S. The effects of laser micro-texturing of the dental implant collar on crestal bone levels and peri-implant health. Int J Oral Maxillofac Implants 2011;26:492–498.
27. Shapoff C, Lahey B, Wasserlauf P, Kim D. Radiographic analysis of crestal bone levels around laser-lok collar dental implants. Int J Periodontics Restorative Dent 2010;30:129–137.
28. Alexander H, Ricci J, Hrico J. A mechanical basis for bone retention around dental implants. J Biomed Mater Res B Appl Biomater 2009;88:306–311.
29. Ketabi M, Pilliar R, Deporter D. Factors driving peri-implant crestal bone loss: A concise literature review and discussion: Part 1. J Implant Adv Clin Dent 2009; 1:19–27.
30. Albrektsson T, Zarb G, Worthington P, Eriksson A. The long-term efficiency of currently used dental implants: A review and proposed criteria of success. Int J Oral Maxillofac Implants 1986;1:11–25.
31. Aalam AA, Nowzari H. Clinical evaluation of dental implants with surfaces roughened by anodic oxidation, dual acid-etched implants and machined implants. Int J Oral Maxillofac Implants 2005; 20:793–798.
32. Chung D, Oh TJ, Lee J, Misch C, Wang HL. Factors affecting late implant bone loss. A retrospective analysis. Int J Oral Maxillofac Implants 2007;22:117–126.
33. Lee DW, Choi YS, Park KH, Kim CS, Moon IS. Effect of micro-thread on the maintenance of marginal bone level: A 3-year prospective study. Clin Oral Implants Res 2007;18:465–470.
34. Bratu E, Tandlich M, Shapira L. A rough surface implant neck with micro-threads reduces the amount of marginal bone loss: A prospective clinical study. Clin Oral Implants Res 2009;20:827–832.
35. Lazzara R, Porter S. Platform switching: A new concept in implant dentistry for controlling post-restorative crestal bone levels. Int J Periodontics Restorative Dent 2006;26:9–17.
36. Shin YK, Han CH, Heo SJ, Kim S, Chun HJ. Radiographic evaluation of marginal bone level around implants with different neck designs after 1 year. Int J Oral Maxillofac Implants 2006;21:789–794.
37. Hansson S. The implant neck: Smooth or provided with retention elements. Clin Oral Implants Res 1999;10:394–405.
38. Maeda Y, Miura J, Taki I, Sogo M. Biomechanical analysis on platform-switching: Is there any biomechanical rationale? Clin Oral Implants Res 2007;18:581–584.
39. Piao C, Lee J, Koak J, et al. Marginal bone loss around three different implant systems: Radiographic evaluation after 1 year. J Oral Rehabil 2009;36:748–754.
40. Rasmussen L, Roos J, Bystedt H. A 10-year follow-up study of titanium dioxide-blasted implants. Clin Implant Dent Rel Res 2005;7:36–42.
41. Jacobs R, Pittayapat P, van Steenberghe D, et al. A split-mouth comparative study up to 16 years of two screw-shaped titanium implant systems. J Clin Periodontol 2010;37:1119–1127.
42. Albrektsson T, Gottlow J, Meirelles L, Ostman PO, Rocci A, Sennerby L. Survival of NobelDirect implants: An analysis of 550 consecutively placed implants at 18 different clinical centers. Clin Implant Dent Relat Res 2007;9:65–70.
43. Albrektsson T, Wennerberg A. Oral implant surfaces: Part I: Review focusing on topographic and chemical properties of different surfaces and in vivo responses to them. Int J Prosthodont 2004;17:536–543.
44. Zetterqvist L, Feldman S, Rotter B, et al. A prospective, multicenter, randomized-controlled 5-year study of hybrid and fully etched implants for the incidence of peri-implantitis. J Periodontol 2010; 81:493–501.
45. Abrahamsson I, Zitzmann N, Berglundh T, Linder E, Wennerberg A, Lindhe J. The mucosal attachment to titanium implants with different surface characteristics: An experimental study in dogs. J Clin Periodontol 2002;29:448–455.
46. Glauser R, Schupbach P, Gottlow J, Hammerle C. Peri-implant soft tissue barrier at experimental one-piece mini-implants with different surface topography in humans: A light-microscopic overview and histometric analysis. Clin Implant Dent Relat Res 2005;7:S44–S51.
47. Berglundh T, Abrahamsson I, Welander M, Lang N, Lindhe J. Morphogenesis of the peri-implant mucosa. An experimental study in dogs. Clin Oral Implants Res 2007;18:1–8.
48. Bates C, Marino V, Fazzalari N, Bartold M. Soft tissue attachment to titanium implants coated with growth factors. Clin Implant Dent Relat Res 2013;15:53–63.
49. Yamano S, Al-Sowygh Z, Gallucci G, Wada K, Weber H-P, Sukotjo C. Early peri-implant tissue reactions on different titanium surface topographies. Clin Oral Implants Res 2011;22:815–819.
50. Dalby M, Riehle M, Johnstone H, Affrossman S, Curtis A. Investigating the limits of filopodial sensing: A brief report using SEM to image the interaction between 10 nm high nano-topography and fibroblast filopodia. Cell Biol Internat 2004; 28:229–236.
51. Wang R, Hsieh MC. Effects of nanometric roughness on surface properties and fibroblast initial cytocompatibilities of Ti-6Al-4V. Biointerphases 2011;6:87–97.