

Clinical relevance of dimensional bone and soft tissue alterations post-extraction in esthetic sites

VIVIANNE CHAPPUIS, MAURICIO G. ARAÚJO & DANIEL BUSER

The development of predictable and innovative implant therapies for optimal esthetic outcomes requires a thorough understanding of the underlying biological processes of bone and soft tissue healing following tooth extraction (16). In the past, research focused on better understanding the osseointegration process, and as a result implant surface topography/chemistry has been profoundly investigated and markedly improved (22, 46, 81, 96). These innovations have contributed to reduced healing periods and the use of short or narrow diameter implants (5, 59). Predictable osseointegration leads to successful implant function over time, which can be assessed by the success criteria proposed by Albrektsson et al. (2), Buser et al. (23) and others. However, successful implant function alone does not fulfill the increasing demands of today's patients and clinicians for pleasing esthetics.

Attaining pleasing esthetics in the anterior maxilla involves many clinical parameters but is principally related to the peri-implant mucosal architecture in comparison with the contra-lateral natural tooth (31). The peri-implant mucosa needs to be supported by an adequate three-dimensional (3D) osseous volume of the alveolar ridge, including an intact facial bone wall of sufficient thickness and height in combination with correct restoration-driven implant positioning (21, 42, 47). Deficiency of the facial bone anatomy has a negative impact on esthetics and is a critical causative factor for esthetic implant complications and failures (28). However, the integrity of the hard and soft tissue dimensions is jeopardized by physiological and structural changes following tooth loss (11). Experimental and clinical research provides important

knowledge about related biological events and the extent of dimensional alterations following tooth extraction, as well as how they can be minimized in order to maintain the natural soft and bone tissue architecture of the dentition over time.

The aim of this review is to summarize the degree of tissue alterations in single tooth extraction sites of the anterior maxilla and to identify associated modulating factors in order to assist the clinician in the selection of the most appropriate treatment protocols to facilitate pleasing esthetic treatment outcomes.

Degree of dimensional tissue alterations following tooth extraction

Bone alterations following tooth extraction

Experimental studies

The dimensional and structural alterations following tooth extraction have been studied in detail in mandibular premolar sites of beagle dogs (8, 25) (Fig. 1). These catabolic changes are initiated by the resorption of the bundle bone that lines the extraction socket. The bundle bone, consisting of lamellar bone, has a thickness of 0.2–0.4 mm and is a tooth-dependent structure (79) (Fig. 1A). The catabolic changes have been correlated with the disruption of the blood supply from the periodontal ligament, which subsequently leads to significant osteoclastic activity (8, 25). As the bundle bone is a tooth-dependent structure, it is gradually resorbed following tooth

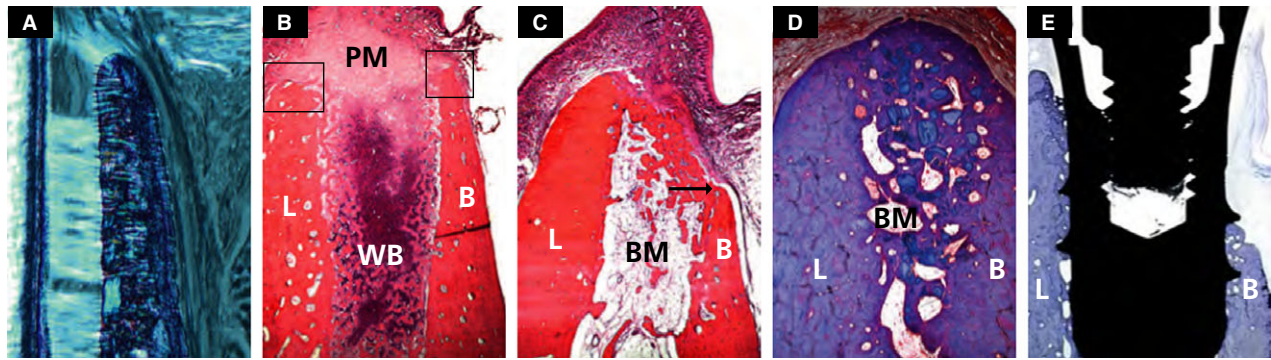


Fig. 1. (A) Buccal-lingual section illustrating the most coronal portion of the buccal bone wall. The buccal wall is made up mainly by bundle bone. Polarized light. Toluidine blue stain; original magnification $\times 50$ (with permission from Ref. (11)). (B) Overview of the extraction site after 2 weeks of healing. Note large amounts of woven bone are present in the lateral and apical portions of the socket. B, buccal; L, lingual; PM, provisional matrix; WB, woven bone. Hematoxylin-eosin staining; original magnification $\times 16$ (with permission from Ref. (8)). (C) Overview of the extraction site after 8 weeks of healing. The entrance of the socket is sealed by a hard tissue ridge that comprises woven bone and lamellar bone. The central portion of the socket is dominated by bone marrow. Note that the marginal portion of the buccal wall (arrow) is about 2 mm 'apical' of the marginal termination of the lingual wall. B,

buccal; BM, bone marrow; L, lingual; arrow, marginal portion of the buccal wall. Hematoxylin-eosin staining; original magnification $\times 16$ (with permission from Ref. (8)). (D) Microphotograph of a buccal-lingual section representing a grafted site. Note the large number of Bio-Oss particles that are present in the healed extraction socket. B, buccal bone wall; BM, bone marrow; L, lingual bone wall. Ladewig fibrin stain; original magnification $\times 7$ (with permission from Ref. (10)). (E) Buccal-lingual section representing an implant site after 3 months of healing. Note the location of the bone crest at the buccal and lingual aspects of the implant. The level of bone-to-implant contact was located 2.6 mm (B, buccal aspect) and 0.2 mm (L, lingual aspect) apical of the sand-blasted and acid-etched level. Toluidine blue staining; original magnification $\times 16$ (with permission from Ref. (12)).

extraction, leading to a vertical bone loss of about 2.2 mm in mandibular premolar sites on the facial aspects (8). In contrast, minimal bone resorption has been observed on the lingual aspect (Fig. 1B,C). This phenomenon has been attributed to the limited thickness of the facial bone wall in comparison with the lingual/palatal aspects of the socket (8). Socket grafting has shown to modify these modeling events and to partially counteract the marginal ridge contraction that occurs following tooth removal (10) (Fig. 1D). Immediate implant insertion into a fresh extraction site failed to prevent the remodeling that occurred in the walls of the socket. The resulting height of the buccal and lingual walls at 3 months was similar at implant and edentulous sites. The vertical bone loss was more pronounced at the buccal than at the lingual aspect of the ridge and amounted to 2.6 mm apical of the sand-blasted and acid-etched level (12) (Fig. 1E). Full maintenance of the facial bone wall dimension has been observed for a bone wall thickness of 2 mm following immediate implant placement in an experimental dog study (74). However, post-extraction dimensional alterations appear to be related to several additional factors, including surgical trauma due to flap elevation, lack of functional stimulus on the remaining bone walls and a lack of periodontal ligament and genetic information (11).

Clinical studies

In humans, dimensional alterations have been reported to cause a ridge width reduction of up to 50% during the first year following tooth loss in premolar and molar sites, where two-thirds of the total changes take place within the first 3 months post-extraction (80). A systematic review showed a loss of 2.6–4.5 mm in width and 0.4–3.9 mm in height of healed sockets (86). The healing events of extraction sockets have also been examined in human biopsies taken at various time points after extraction (88). It was shown that the density of vascular structures and macrophages slowly decreased from 2 to 4 weeks, the level of osteoclastic activity slowly decreased over a 4-week period, whereas the presence of osteoblasts peaked at 6–8 weeks and remained almost stable thereafter.

The extent of bone loss following extraction seems to depend on factors such as facial bone wall thickness, angulation of the tooth, and other differences in anatomy at the various tooth sites (66). The width of the facial socket wall is either analysed intraoperatively 1 mm below the alveolar crest (52), or measured by cone beam computed tomography at different levels (18, 55, 89). The facial bone wall thickness in the anterior maxilla has been shown to be less than 1 mm in 90% of cases and less than 0.5 mm in

almost 50% of cases (18, 52, 55, 89). Hence, such thin facial bone walls, consisting mainly of bundle bone, appear to be prone to resorption following tooth extraction. In a clinical cone beam computed tomography study of 39 patients, a progressive bone resorption pattern was observed in sites with a facial bone wall thickness of 1 mm or less, leading to a median vertical bone loss of 7.5 mm or 62% of the former facial bone height after 8 weeks of healing (26) (Fig. 2). In contrast, patients with a thick wall phenotype, showing a facial bone wall thickness of more than 1 mm, displayed only a median vertical bone loss of 1.1 mm or 9%. The dimensional alteration pattern in single extraction sites with healthy neighboring dentition occurred mainly in the central area of the socket wall, whereas the proximal areas remained nearly unchanged after flapless tooth extraction at 8 weeks of healing (Fig. 2).

Clinical recommendations regarding dimensional bone alteration

The assessment of the facial bone wall thickness provides the clinician with a prognostic tool to estimate

the degree of future bone loss prior to tooth extraction. It is important to note that dimensional bone alterations observed in patients are 2–3.5 times more severe than those seen in experimental studies (3, 8, 12, 26, 37, 92). Post-extraction bone modeling in single-tooth extraction sites seems to be localized to the central, mid-facial aspect of the socket wall at 8 weeks post-extraction, while proximal areas are well supported by the periodontal ligament (PDL) of the neighboring teeth and show no bone loss (28). Such a bone resorption pattern results in a two-wall defect morphology in thin bone wall phenotypes in which the facial bone wall has been partially resorbed, and in a three-wall morphology in sites with an intact thick facial bone wall phenotype (26). The high regenerative potential of two- and three-wall peri-implant bone defects has been attributed to the ratio between the area of exposed bone marrow and the defect volume to be regenerated (77). As discussed earlier, studies have shown that the initial osteoclastic activity decreased at 8 weeks, whereas the osteoblastic activity remains high (8, 25, 88), providing favorable conditions for regenerative procedures (19, 76). Therefore,

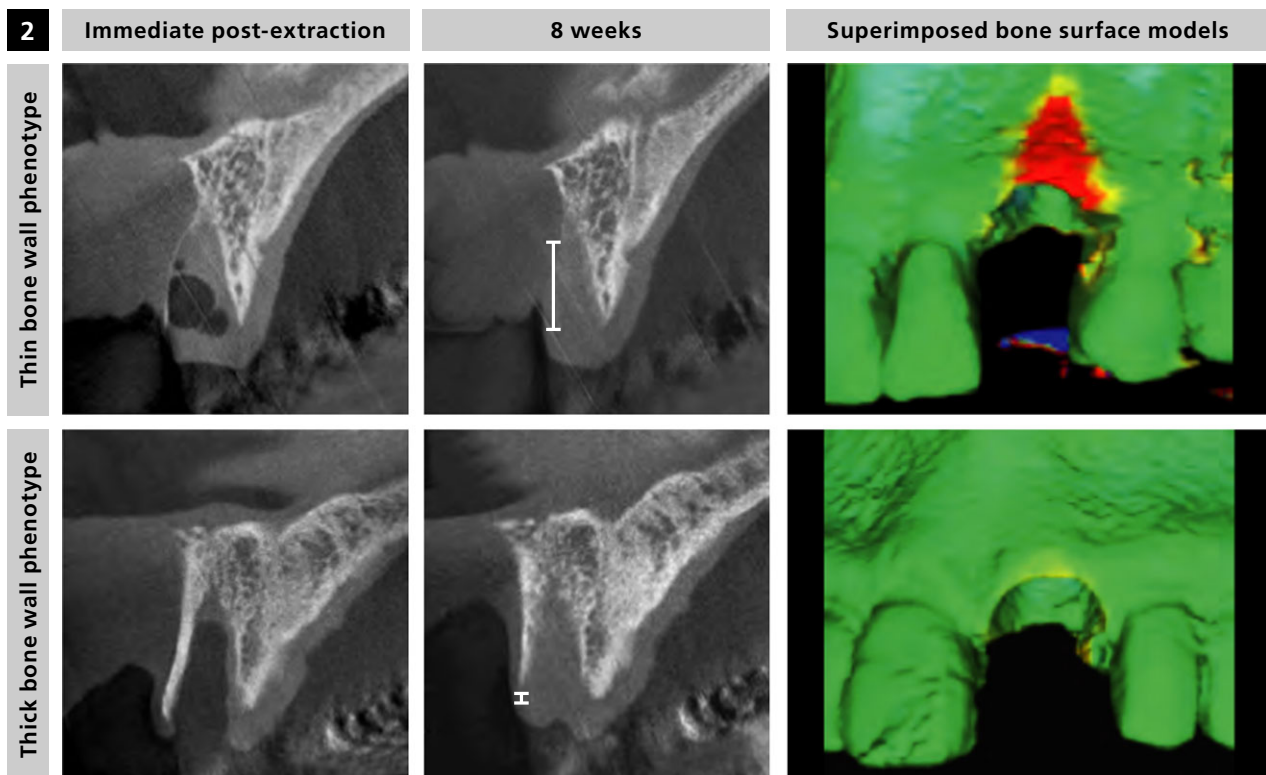


Fig. 2. Thin bone wall phenotypes with a facial bone wall thickness of 1 mm or less, revealed a progressive bone resorption pattern, leading to median vertical bone loss of 7.5 mm or 62% of the former facial bone height after 8 weeks of healing. This is in contrast to thick wall phenotypes, showing a facial bone wall thickness of more than 1 mm, displaying only a

median vertical bone loss of 1.1 mm or 9%. The dimensional alteration pattern in single extraction sites with healthy neighboring dentition occurred mainly in the central area of the socket wall, whereas the proximal areas remained nearly unchanged after flapless tooth extraction at 8 weeks of healing (with permission from Ref. (26)).

in thin bone wall phenotypes, the initial and physiological post-extraction bone modeling phase should be waited for, in order to facilitate bone regenerative procedures. This protocol has been adopted for early implant placement, where a healing period of 4–16 weeks is used prior to implant insertion (50), and has been recommended as the treatment of choice in sites exhibiting a progressive bone resorption pattern, such as the thin bone wall phenotypes (67). An immediate implant placement protocol can be recommended in thick bone wall phenotypes and thick gingival biotypes, where the post-extraction bone modeling is expected to be minimal (67). However, if such ideal conditions are not present, other implant timing protocols are recommended in order to provide predictable esthetic treatment outcomes (67, 94).

Soft tissue alterations following tooth extraction

Soft tissue dimensions prior to tooth extraction

Even though the soft tissue texture, color and appearance plays a pivotal role in achieving pleasing esthetics (15), the influence of soft tissue healing in post-extraction sites has received little attention in clinical research (82). Thicker soft tissues not only have a higher volume of extracellular matrix and collagen, but also increased vascularity, which enhances the clearance of toxic products and favors the immune response (53, 70). Therefore, thicker soft tissues have been shown to respond more favorably to wound healing, flap management and restorative trauma, not only in periodontal (53) but also in implant surgery (35, 91). Prior to extraction, the facial soft tissue thickness in the anterior maxilla by nature is thin in most patients, ranging between 0.5 and 1 mm (41, 68, 83). No significant correlation has been found between soft tissue thickness and the underlying facial bone wall thickness (27, 40, 99). Several surgical techniques have been developed to effectively increase the soft tissue volume and are routinely used by clinicians (58, 87).

Soft tissue dimension post-extraction

As in fracture repair, wound healing of extraction sockets is a complex process that requires spatially and temporarily regulated expression as well as coordinated interplay between many different types of tissues and cells (43, 48, 61). The current understanding of soft tissue healing and regenerative strategies is mainly based on cutaneous wounds (70). In contrast to cutaneous wounds, mucosal wounds heal with only minimal scar formation and exhibit an accelerated healing pattern (45, 84, 85). The favorable

healing of the oral mucosa is characterized by a faster resolution of inflammation and control of myofibroblast action compared with skin wounds (64). Extracellular matrix components revealed similarities between oral and fetal tissue, which eventually play a role in the favorable healing events between these two tissues (44). This might indicate that some extracellular matrix components are involved in the mode of repair. However, knowledge of dimensional alterations of the overlying facial soft tissues is scarce and their contribution to post-extraction bone modeling is poorly understood (27).

Dimensional soft tissue changes post-extraction have been examined in single tooth extraction sites (27). Overall, more than 50% of these changes occur very quickly, within 2 weeks of healing. The soft tissue thickness increases significantly depending on the underlying bone dimensions (27) (Fig. 3). In thick-wall phenotypes, the alveolus provides a self-contained bony defect, which favors the ingrowth of progenitor cells from the bony socket walls and the surrounding bone marrow space. In such thick bone wall phenotypes, the soft tissue dimensions on the facial aspect remain unchanged during healing (27) (Fig. 3). This is in contrast to thin bone wall phenotypes, in which the soft tissue dimensions revealed a sevenfold spontaneous increase after healing which was termed spontaneous soft tissue thickening (Fig. 3). It may be hypothesized that the rapidly resorbing thin facial bone wall favors facial soft tissue ingrowth due to its high proliferative rate. Subsequently, these soft tissue cells occupy the majority of the available space in the crestal area of an extraction socket defect. A highly vascularized granulation tissue is formed and fibroblasts migrate into the wound (48). Some of these fibroblasts differentiate into myofibroblasts, which stabilize wound margins and may be involved in the thickening phenomenon (60). A trend toward soft tissue thickening following tooth extraction has also been shown in other studies (36, 54, 56, 78). On a molecular level, soft tissue thickening at 8 weeks is paralleled by a peak in endothelial cell density, in bone morphogenetic protein-7 and in osteocalcin expression (88). Therefore, the molecular and cellular mechanisms that control new bone formation may also influence soft tissue thickening (1, 43).

Clinical recommendations regarding dimensional soft tissue alterations

The facial soft tissue thickens spontaneously in sites where progressive bone resorption of the former socket walls occurs (27). This spontaneous soft tissue thickening in thin bone wall phenotypes after an 8-

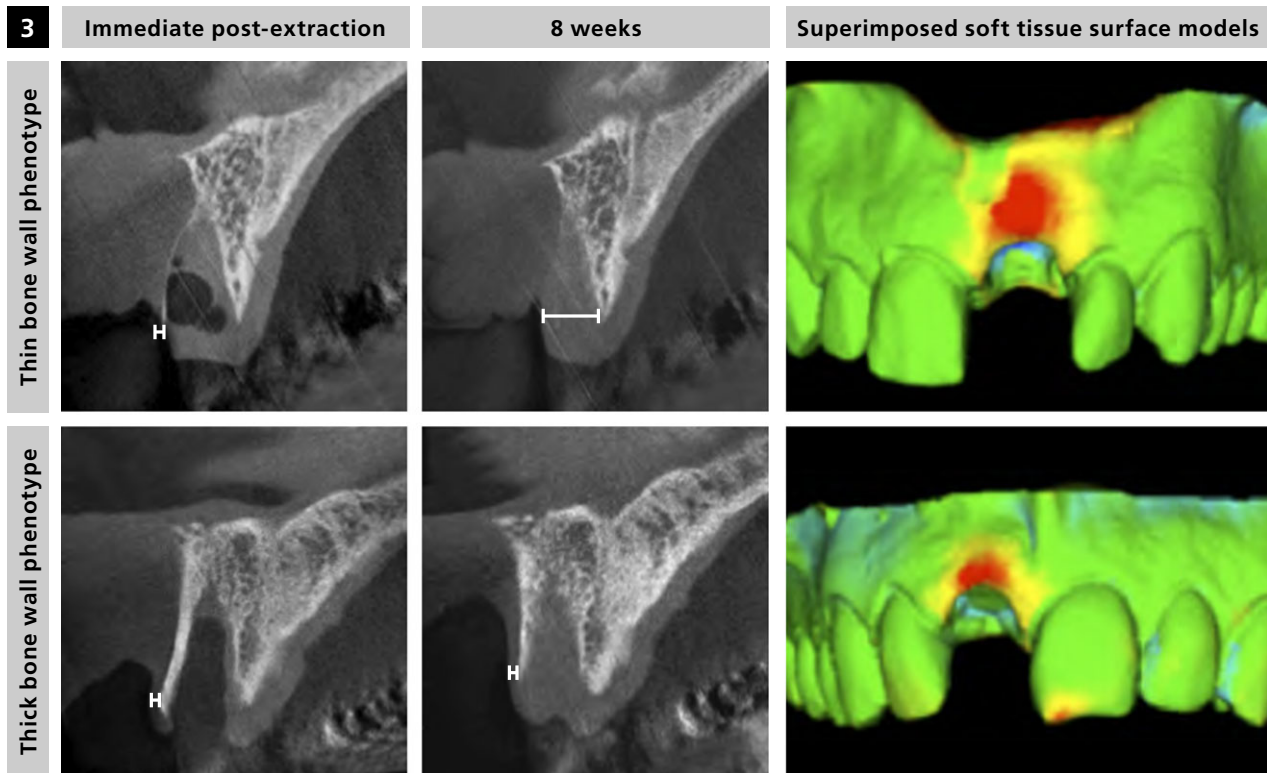


Fig. 3. In thick-wall phenotypes, the alveolus provides a self-contained bony defect, which favors the ingrowth of progenitor cells from the bony socket walls and the surrounding bone marrow space. In such thick bone wall phenotypes, the soft tissue dimensions on the facial aspect remain unchanged during healing. This is in contrast to thin bone wall phenotypes, in which the soft tissue dimensions revealed a sevenfold

spontaneous increase after healing, which was termed spontaneous soft tissue thickening. It may be hypothesized that the rapidly resorbing thin facial bone wall favors facial soft tissue ingrowth due to its high proliferative rate. Subsequently, these soft tissue cells occupy the majority of the available space in the crestal area of an extraction socket defect (with permission from Ref. (27)).

week healing period offers several advantages during implant surgery. First, the spontaneous soft tissue coverage after healing provides an increased amount of keratinized mucosa, which facilitates primary flap closure and favors bone regeneration (19, 35, 71, 98). Second, the spontaneously thickened soft tissue volume may reduce the need for additional soft tissue grafting, limiting morbidity and treatment costs. However, these spontaneously thickened tissues may mask the true extent of an underlying bone defect during the clinical examination and may subsequently mislead clinicians in the selection of the appropriate treatment protocol (67).

Factors influencing the degree of dimensional alterations

Over the past two decades it has become evident that post-extraction dimensional alterations inevitably occur due to the resorption of the bundle bone as a tooth-dependent structure, and to related factors such

as a lack of functional stimulus and a lack of vascular blood supply due to the missing periodontal ligament and genetic information (11). Even though numerous bone and soft tissue augmentation techniques have been suggested for regenerating the lost tissue structures (65), establishing clear guidelines for facilitating implant placement and achieving predictable treatment outcomes remain a significant challenge in clinical practice (13). Several surgical techniques have the potential to modulate the degree of these inevitable changes, such as flapless tooth extraction, ridge preservation and immediate implant placement.

Flapless tooth extraction

Even though tooth extraction has been considered a simple and straightforward procedure, it should be performed with care and under the assumption that dimensional ridge alterations will follow (11). Tooth extraction is an invasive procedure, since it disrupts vascular structures and damages soft tissues and the associated periodontal ligament (25). Flapless tooth

extraction is important to avoid additional bone resorption from the bony surface related to the elevation of the mucoperiosteal flap (97). Flapless tooth extraction has been shown to reduce the amount of bone loss in the early healing phase 4–8 weeks post-extraction compared with full-thickness flap elevations (38), whereas after a healing period of 6 months, no differences were observed regarding bone loss with or without flap elevation (9). Therefore, a flapless low-trauma tooth extraction approach is recommended in cases of immediate implant placement in sockets with thick facial bone wall phenotypes and when using early implant placement protocols (Type 2, 3) in order to avoid additional bone loss at the superficial bone wall (20, 50). The extraction itself should be performed without applying force toward the thin facial bone wall. Several new surgical instruments and approaches are available to promote low-trauma tooth extraction, such as periostomes, piezosurgery and vertical tooth extraction devices (69, 90). If these techniques are not applicable, a separation along the longitudinal root axis in the oro-facial direction is recommended in order to minimize pressure on the facial bone wall and to make it possible to remove the root fragments separately.

Ridge preservation techniques

Even though attempts to preserve the ridge have failed to arrest the inevitable biological process of dimensional ridge alterations post-extraction, in particular with respect to the preservation of the alveolar bone volume, studies have shown that grafting of extraction sockets with biomaterials and the use of barrier membranes is able to reduce the degree of dimensional alterations (7, 10, 13).

Maintenance of the root

Early therapeutic attempts to prevent alveolar ridge resorption were performed using root retention, with the primary goal of maximizing the stability of removable prostheses (72). Clinical studies have tested the hypothesis that root retention by decoronation of the crown at the bone level is able to reduce ridge alterations and to maintain existing bone volume dimensions (4, 39). Other authors have suggested maintaining a facial shield of a root remnant simultaneously with implant placement, with the aim of preserving the facial bone architecture (14, 51). However, root retention with simultaneous implant placement is rarely feasible due to infection, fracture, or decay of the affected tooth or for strategic reasons. If compromised roots are maintained in close contact with an

implant they may cause severe damage to the neighboring implants (62).

Socket grafting

Socket grafting has gained in popularity in recent years due to its conceptual attractiveness and technical simplicity (30). A large variety of biomaterials have been employed and tested in several studies, including autologous bone, bone substitutes (allografts, xenografts and alloplasts), autologous blood-derived products and bioactive agents (34). An experimental study demonstrated that in untreated extraction sockets, about 50–60% of the tissue was newly mineralized bone after 3 months of healing, whereas in sites grafted using deproteinized bovine bone mineral only 12% of the former socket was occupied by newly mineralized tissue (6). This implies that new bone formation is delayed in the earlier healing phase in grafted sites. A recent randomized clinical trial in 14 patients revealed that socket grafting failed to preserve the resorption of the buccal and palatal bone walls after 4 months of healing. However, the deproteinized bovine bone mineral particles were integrated with the newly formed host bone and retained the volume of the hard tissue defect, although the buccal and to some extent also the palatal bone plates were markedly diminished (7). The Osteology Consensus Conference in 2012 concluded that the majority of studies and systematic reviews did not reveal significant differences between various biomaterials and treatment approaches. Although primary wound closure was considered an important factor, the literature did not allow for a meaningful comparison of different techniques (49). A recent systematic review revealed that wound closure, the use of a membrane and the application of a xenograft or an allograft resulted in better outcomes than unassisted healing, showing a mean effect of 1.9 mm in terms of bucco-lingual width and 2.1 mm for the mid-buccal height (13) (Fig. 4).

Immediate implant placement

It has been suggested that placement of implants into fresh extraction sockets with a bone-to-implant gap of 2 mm or less would prevent remodeling and hence maintain the original shape of the ridge (73). However, findings reported from a clinical study by Botticelli et al. (17) failed to support this hypothesis. After 4 months of healing the outer surface of the buccal and lingual bone walls was markedly diminished, with a mean reduction of 56% in the buccal aspect and 30% in the lingual aspect. These findings were supported by an experimental study revealing a

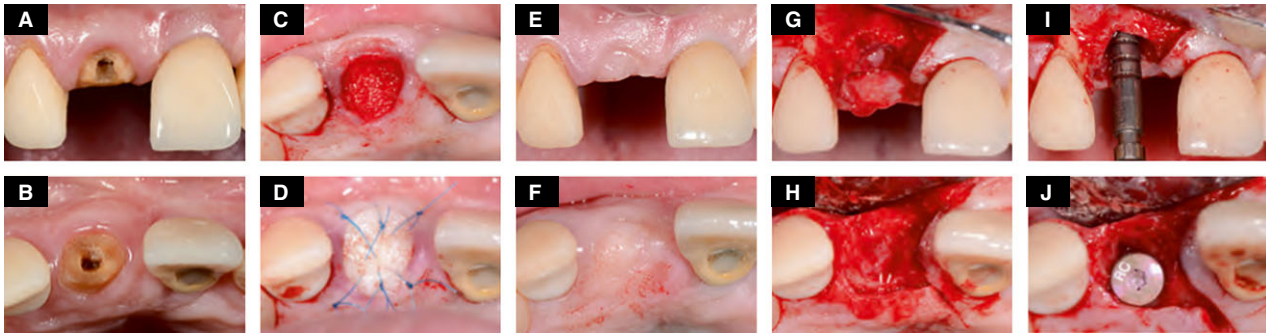


Fig. 4. A longitudinal fracture occurred in the right central incisor, which necessitated root removal. Adjacent to the fractured root a single implant restoration is already present (A, B). In order to limit dimensional alterations a socket grafting approach was chosen. The root was removed by a flapless low-trauma tooth extraction technique and the socket was grafted using Bio-Oss collagen

(Geistlich Pharma, Wohlen, Switzerland) (C). A free gingival graft was harvested from the palate, carefully adapted and sutured (D). After 4 months of healing the grafted site revealed pleasing soft tissue conditions (E, F) and a partially preserved former extraction socket (G, H). The site allowed correct restoration driven implant placement (I, J) including subsequent contour augmentation.

vertical bone loss of the facial bone wall of, on average 2.6 mm after a 12-week healing period (12). Recent animal studies evaluated the effect on facial bone wall resorption of either a new nano-topography at the implant surface or microgrooves at the implant neck. Both studies revealed that neither the modified surface topography nor the implant design had a significant effect in limiting the facial bone wall resorption in immediate implant placement protocols (3, 92). Root-shaped implant designs have been proposed to reduce the gap between the implant surface and the former socket walls and thus to prevent bone loss. In contrast, wide root-shaped implants occupying most of the socket caused more pronounced alveolar bone resorption (24). In addition to immediate implant placement, simultaneous contour augmentation using deproteinized bovine bone mineral particles was performed in an experimental study. After 3 months of healing the buccal bone was not maintained but showed an average resorption of 2.3 mm (37).

Two recent clinical studies involving consecutive cone beam computed tomography at implant placement and after 1 year confirmed that significant mid-facial vertical bone resorption occurred in immediate implant cases (75, 89). Recent systematic reviews demonstrated that predictable results are difficult to obtain and that these techniques show an increased risk of significant mucosal recession if this approach is not applied with strict inclusion criteria (29, 33, 57). Following immediate implant placement, mid-facial recession exceeding 1 mm occurs in 9–41% of sites after 1–3 years (28). Other surgical factors, such as the use of a flapless technique, immediate provisional restorations, the applications of soft-tissue grafts or the use of implant-

abutment connections with a platform-switching concept are still controversial because there is still no clear evidence for their efficacy (94). These need to be further investigated in well-designed clinical trials.

Clinical recommendations

In general, preservation of an extraction socket is indicated if immediate or early implant placement is not feasible due to patient- or site-specific indications. Patient-specific indications for ridge preservation techniques are (i) too young (age < 20 years) and (ii) treatment postponed for medical, financial or social reasons. Site-specific indications are related to the severity of the bone defect at the extraction site. Extensive defects require partial bone healing in order to later achieve sufficient primary stability of the implant in a correct 3D implant position. Sites associated with extensive soft tissue defects may require soft tissue grafting in order to improve keratinization and/or soft tissue volume prior to implant placement.

Maintenance of the root until the start of implant treatment is an easy and economical approach, but can only be recommended for roots without an acute or chronic inflammation, decay or a longitudinal fracture. Soft tissue closure of the extraction socket combined with the use of biomaterials with a low substitution rate is advisable, as this seems to retain the tissue volume at the site (13, 34, 49, 86, 93, 95).

Immediate implant placement does not prevent bone resorption *per se* and should only be used in sites where post-extraction bone modeling is expected to be minimal, such as with a thick bone wall phenotype (> 1 mm) and thick gingival biotype, as recommended by the 2013 International Team for Implantology (ITI) consensus conference (67). The

facial bone wall of a former extraction socket can be maintained with an immediate implant placement protocol if strict patient inclusion criteria and appropriate techniques are applied (32, 63). If ideal conditions are not present, other implant timing protocols are preferred to achieve predictable esthetic outcomes (67, 94).

Conclusions

The dimensional bone and soft tissue alterations following tooth extraction in the anterior maxilla have a significant impact on the esthetic outcome of implant-supported restorations. Research has shown that significant bone modeling activities occur during the first 2 weeks of healing. Bone modeling in single extraction sites is mainly localized to the central aspect of the facial bone wall, whereas proximal aspects are well maintained by the periodontal ligaments of the adjacent teeth. The extent of flapless post-extraction bone modeling depends on the facial bone wall thickness. Whereas thin bone wall phenotypes (< 1 mm) often show a progressive bone resorption pattern with extensive vertical loss of the former socket wall, thick bone wall phenotypes (> 1 mm) show only limited resorption rates. Regarding dimensional soft tissue alterations, the facial soft tissue thickness does not necessarily correlate with the underlying bone wall dimensions. For thin bone wall phenotypes, extraction leads to spontaneous soft tissue thickening by a factor of seven, while no significant changes are seen for thick bone wall phenotypes. Finally, soft tissue thickening in thin bone wall phenotypes may mask the true extent of the underlying defect, which may mislead the clinician during the clinical examination. Neither ridge preservation techniques nor immediate implant placement prevents physiological bone modeling activity after tooth extraction. Therefore, tooth extraction should be performed with the understanding that ridge reduction will follow, and further clinical steps should be considered to compensate for such changes when considering replacement of the extracted tooth with an implant-supported restoration.

References

1. Ai-Aql ZS, Alagl AS, Graves DT, Gerstenfeld LC, Einhorn TA. Molecular mechanisms controlling bone formation during fracture healing and distraction osteogenesis. *J Dent Res* 2008; **87**: 107–118.
2. Albrektsson T, Zarb G, Worthington P, Eriksson AR. The long-term efficacy of currently used dental implants: a review and proposed criteria of success. *Int J Oral Maxillofac Implants* 1986; **1**: 11–25.
3. Alharbi HM, Babay N, Alzoman H, Basudan S, Anil S, Jansen JA. Bone morphology changes around two types of bone-level implants installed in fresh extraction sockets – a histomorphometric study in Beagle dogs. *Clin Oral Implants Res* 2015; **26**: 1106–1112.
4. Andersson L, Emami-Kristiansen Z, Hogstrom J. Single-tooth implant treatment in the anterior region of the maxilla for treatment of tooth loss after trauma: a retrospective clinical and interview study. *Dent Traumatol* 2003; **19**: 126–131.
5. Annibaldi S, Cristalli MP, Dell'Aquila D, Bignozzi I, La Monaca G, Pilloni A. Short dental implants: a systematic review. *J Dent Res* 2012; **91**: 25–32.
6. Araujo M, Linder E, Wennstrom J, Lindhe J. The influence of Bio-Oss collagen on healing of an extraction socket: an experimental study in the dog. *Int J Periodontics Restorative Dent* 2008; **28**: 123–135.
7. Araujo MG, da Silva JC, de Mendonca AF, Lindhe J. Ridge alterations following grafting of fresh extraction sockets in man. A randomized clinical trial. *Clin Oral Implants Res* 2015; **26**: 407–412.
8. Araujo MG, Lindhe J. Dimensional ridge alterations following tooth extraction: an experimental study in the dog. *J Clin Periodontol* 2005; **32**: 212–218.
9. Araujo MG, Lindhe J. Ridge alterations following tooth extraction with and without flap elevation: an experimental study in the dog. *Clin Oral Implants Res* 2009; **20**: 545–549.
10. Araujo MG, Lindhe J. Ridge preservation with the use of Bio-Oss collagen: a 6-month study in the dog. *Clin Oral Implants Res* 2009; **20**: 433–440.
11. Araujo MG, Silva CO, Misawa M, Sukekava F. Alveolar socket healing: what can we learn? *Periodontol* 2000 2015; **68**: 122–134.
12. Araujo MG, Sukekava F, Wennstrom JL, Lindhe J. Ridge alterations following implant placement in fresh extraction sockets: an experimental study in the dog. *J Clin Periodontol* 2005; **32**: 645–652.
13. Avila-Ortiz G, Elangovan S, Kramer KW, Blanchette D, Dawson DV. Effect of alveolar ridge preservation after tooth extraction: a systematic review and meta-analysis. *J Dent Res* 2014; **93**: 950–958.
14. Baumer D, Zuhr O, Rebele S, Schneider D, Schupbach P, Hurzeler M. The socket-shield technique: first histological, clinical, and volumetric observations after separation of the buccal tooth segment – a pilot study. *Clin Implant Dent Relat Res* 2015; **17**: 71–82.
15. Belser UC, Buser D, Hess D, Schmid B, Bernard JP, Lang NP. Aesthetic implant restorations in partially edentulous patients – a critical appraisal. *Periodontol* 2000 1998; **17**: 132–150.
16. Berglundh T, Giannobile WV. Investigational clinical research in implant dentistry: beyond observational and descriptive studies. *J Dent Res* 2013; **92**: 107S–108S.
17. Botticelli D, Berglundh T, Lindhe J. Hard-tissue alterations following immediate implant placement in extraction sites. *J Clin Periodontol* 2004; **31**: 820–828.
18. Braut V, Bornstein MM, Belser U, Buser D. Thickness of the anterior maxillary facial bone wall – a retrospective

- radiographic study using cone beam computed tomography. *Int J Periodontics Restorative Dent* 2011; **31**: 125–131.
19. Buser D, Bornstein MM, Weber HP, Grutter L, Schmid B, Belser UC. Early implant placement with simultaneous guided bone regeneration following single-tooth extraction in the esthetic zone: a cross-sectional, retrospective study in 45 subjects with a 2- to 4-year follow-up. *J Periodontol* 2008; **79**: 1773–1781.
 20. Buser D, Chen ST, Weber HP, Belser UC. Early implant placement following single-tooth extraction in the esthetic zone: biologic rationale and surgical procedures. *Int J Periodontics Restorative Dent* 2008; **28**: 441–451.
 21. Buser D, Martin W, Belser UC. Optimizing esthetics for implant restorations in the anterior maxilla: anatomic and surgical considerations. *Int J Oral Maxillofac Implants* 2004; **19** (Suppl.): 43–61.
 22. Buser D, Nydegger T, Hirt HP, Cochran DL, Nolte LP. Removal torque values of titanium implants in the maxilla of miniature pigs. *Int J Oral Maxillofac Implants* 1998; **13**: 611–619.
 23. Buser D, Weber HP, Lang NP. Tissue integration of non-submerged implants. 1-year results of a prospective study with 100 ITI hollow-cylinder and hollow-screw implants. *Clin Oral Implants Res* 1990; **1**: 33–40.
 24. Caneva M, Salata LA, de Souza SS, Bressan E, Botticelli D, Lang NP. Hard tissue formation adjacent to implants of various size and configuration immediately placed into extraction sockets: an experimental study in dogs. *Clin Oral Implants Res* 2010; **21**: 885–890.
 25. Cardaropoli G, Araujo M, Lindhe J. Dynamics of bone tissue formation in tooth extraction sites. An experimental study in dogs. *J Clin Periodontol* 2003; **30**: 809–818.
 26. Chappuis V, Engel O, Reyes M, Shahim K, Nolte LP, Buser D. Ridge alterations post-extraction in the esthetic zone: a 3D analysis with CBCT. *J Dent Res* 2013; **92**: 195S–201S.
 27. Chappuis V, Engel O, Shahim K, Reyes M, Katsaros C, Buser D. Soft tissue alterations in esthetic postextraction sites: a 3-dimensional analysis. *J Dent Res* 2015; **94**: 187S–193S.
 28. Chen ST, Buser D. Clinical and esthetic outcomes of implants placed in postextraction sites. *Int J Oral Maxillofac Implants* 2009; **24** (Suppl.): 186–217.
 29. Chen ST, Buser D. Esthetic outcomes following immediate and early implant placement in the anterior maxilla – a systematic review. *Int J Oral Maxillofac Implants* 2014; **29** (Suppl.): 186–215.
 30. Christensen GJ. Ridge preservation: why not? *J Am Dent Assoc* 1996; **127**: 669–670.
 31. Cooper LF. Objective criteria: guiding and evaluating dental implant esthetics. *J Esthet Restor Dent* 2008; **20**: 195–205.
 32. Cooper LF, Reside GJ, Raes F, Garriga JS, Tarrida LG, Wiltfang J, Kern M, De Bruyn H. Immediate provisionalization of dental implants placed in healed alveolar ridges and extraction sockets: a 5-year prospective evaluation. *Int J Oral Maxillofac Implants* 2014; **29**: 709–717.
 33. Cosyn J, Hooghe N, De Bruyn H. A systematic review on the frequency of advanced recession following single immediate implant treatment. *J Clin Periodontol* 2012; **39**: 582–589.
 34. Darby I, Chen ST, Buser D. Ridge preservation techniques for implant therapy. *Int J Oral Maxillofac Implants* 2009; **24** (Suppl.): 260–271.
 35. Evans CD, Chen ST. Esthetic outcomes of immediate implant placements. *Clin Oral Implants Res* 2008; **19**: 73–80.
 36. Farmer M, Darby I. Ridge dimensional changes following single-tooth extraction in the aesthetic zone. *Clin Oral Implants Res* 2014; **25**: 272–277.
 37. Favero G, Lang NP, Romanelli P, Pantani F, Caneva M, Botticelli D. A digital evaluation of alveolar ridge preservation at implants placed immediately into extraction sockets: an experimental study in the dog. *Clin Oral Implants Res* 2015; **26**: 102–108.
 38. Fickl S, Zuhr O, Wachtel H, Bolz W, Huerzeler M. Tissue alterations after tooth extraction with and without surgical trauma: a volumetric study in the beagle dog. *J Clin Periodontol* 2008; **35**: 356–363.
 39. Filippi A, Pohl Y, von Arx T. Decoronation of an ankylosed tooth for preservation of alveolar bone prior to implant placement. *Dent Traumatol* 2001; **17**: 93–95.
 40. Frost NA, Mealey BL, Jones AA, Huynh-Ba G. Periodontal biotype: gingival thickness as it relates to probe visibility and buccal plate thickness. *J Periodontol* 2015; **86**: 1141–1149.
 41. Fu JH, Yeh CY, Chan HL, Tatarakis N, Leong DJ, Wang HL. Tissue biotype and its relation to the underlying bone morphology. *J Periodontol* 2010; **81**: 569–574.
 42. Garber DA, Belser UC. Restoration-driven implant placement with restoration-generated site development. *Compend Contin Educ Dent* 1995; **16**: 796, 798–802, 804.
 43. Gerstenfeld LC, Cullinane DM, Barnes GL, Graves DT, Einhorn TA. Fracture healing as a post-natal developmental process: molecular, spatial, and temporal aspects of its regulation. *J Cell Biochem* 2003; **88**: 873–884.
 44. Glim JE, Everts V, Niessen FB, Ulrich MM, Beelen RH. Extracellular matrix components of oral mucosa differ from skin and resemble that of foetal skin. *Arch Oral Biol* 2014; **59**: 1048–1055.
 45. Glim JE, van Egmond M, Niessen FB, Everts V, Beelen RH. Detrimental dermal wound healing: what can we learn from the oral mucosa? *Wound Repair Regen* 2013; **21**: 648–660.
 46. Gotfredsen K, Berglundh T, Lindhe J. Anchorage of titanium implants with different surface characteristics: an experimental study in rabbits. *Clin Implant Dent Relat Res* 2000; **2**: 120–128.
 47. Grunder U, Gracis S, Capelli M. Influence of the 3-D bone-to-implant relationship on esthetics. *Int J Periodontics Restorative Dent* 2005; **25**: 113–119.
 48. Gurtner GC, Werner S, Barrandon Y, Longaker MT. Wound repair and regeneration. *Nature* 2008; **453**: 314–321.
 49. Hammerle CH, Araujo MG, Simion M, Osteology Consensus G. Evidence-based knowledge on the biology and treatment of extraction sockets. *Clin Oral Implants Res* 2012; **23** (Suppl. 5): 80–82.
 50. Hammerle CH, Chen ST, Wilson TG Jr. Consensus statements and recommended clinical procedures regarding the placement of implants in extraction sockets. *Int J Oral Maxillofac Implants* 2004; **19** (Suppl.): 26–28.
 51. Huerzeler MB, Zuhr O, Schupbach P, Rebele SF, Emmanouilidis N, Fickl S. The socket-shield technique: a proof-of-principle report. *J Clin Periodontol* 2010; **37**: 855–862.
 52. Huynh-Ba G, Pjetursson BE, Sanz M, Cecchinato D, Ferrus J, Lindhe J, Lang NP. Analysis of the socket bone wall dimensions in the upper maxilla in relation to immediate implant placement. *Clin Oral Implants Res* 2010; **21**: 37–42.

53. Hwang D, Wang HL. Flap thickness as a predictor of root coverage: a systematic review. *J Periodontol* 2006; **77**: 1625–1634.
54. Iasella JM, Greenwell H, Miller RL, Hill M, Drisko C, Bohra AA, Scheetz JP. Ridge preservation with freeze-dried bone allograft and a collagen membrane compared to extraction alone for implant site development: a clinical and histologic study in humans. *J Periodontol* 2003; **74**: 990–999.
55. Januario AL, Duarte WR, Barriviera M, Mesti JC, Araujo MG, Lindhe J. Dimension of the facial bone wall in the anterior maxilla: a cone-beam computed tomography study. *Clin Oral Implants Res* 2011; **22**: 1168–1171.
56. Jung RE, Fenner N, Hammerle CH, Zitzmann NU. Long-term outcome of implants placed with guided bone regeneration (GBR) using resorbable and non-resorbable membranes after 12–14 years. *Clin Oral Implants Res* 2013; **24**: 1065–1073.
57. Kan JY, Rungcharassaeng K, Lozada JL, Zimmerman G. Facial gingival tissue stability following immediate placement and provisionalization of maxillary anterior single implants: a 2- to 8-year follow-up. *Int J Oral Maxillofac Implants* 2011; **26**: 179–187.
58. Kan JY, Rungcharassaeng K, Morimoto T, Lozada J. Facial gingival tissue stability after connective tissue graft with single immediate tooth replacement in the esthetic zone: consecutive case report. *J Oral Maxillofac Surg* 2009; **67**: 40–48.
59. Klein MO, Schiegnitz E, Al-Nawas B. Systematic review on success of narrow-diameter dental implants. *Int J Oral Maxillofac Implants* 2014; **29** (Suppl.): 43–54.
60. Klingberg F, Hinz B, White ES. The myofibroblast matrix: implications for tissue repair and fibrosis. *J Pathol* 2013; **229**: 298–309.
61. Lalani Z, Wong M, Brey EM, Mikos AG, Duke PJ. Spatial and temporal localization of transforming growth factor-beta1, bone morphogenetic protein-2, and platelet-derived growth factor-A in healing tooth extraction sockets in a rabbit model. *J Oral Maxillofac Surg* 2003; **61**: 1061–1072.
62. Langer L, Langer B, Salem D. Unintentional root fragment retention in proximity to dental implants: a series of six human case reports. *Int J Periodontics Restorative Dent* 2015; **35**: 305–313.
63. Lee EA, Gonzalez-Martin O, Fiorellini J. Lingualized flapless implant placement into fresh extraction sockets preserves buccal alveolar bone: a cone beam computed tomography study. *Int J Periodontics Restorative Dent* 2014; **34**: 61–68.
64. Mak K, Manji A, Gallant-Behm C, Wiebe C, Hart DA, Larjava H, Hakkinen L. Scarless healing of oral mucosa is characterized by faster resolution of inflammation and control of myofibroblast action compared to skin wounds in the red Duroc pig model. *J Dermatol Sci* 2009; **56**: 168–180.
65. McAllister BS, Haghighat K. Bone augmentation techniques. *J Periodontol* 2007; **78**: 377–396.
66. Misawa M, Lindhe J, Araujo MG. The alveolar process following single-tooth extraction: a study of maxillary incisor and premolar sites in man. *Clin Oral Implants Res* 2016; **27**: 884–889.
67. Morton D, Chen ST, Martin WC, Levine RA, Buser D. Consensus statements and recommended clinical procedures regarding optimizing esthetic outcomes in implant dentistry. *Int J Oral Maxillofac Implants* 2014; **29** (Suppl.): 216–220.
68. Muller HP, Heinecke A, Schaller N, Eger T. Masticatory mucosa in subjects with different periodontal phenotypes. *J Clin Periodontol* 2000; **27**: 621–626.
69. Muska E, Walter C, Knight A, Taneja P, Bulsara Y, Hahn M, Desai M, Dietrich T. Atraumatic vertical tooth extraction: a proof of principle clinical study of a novel system. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2013; **116**: e303–e310.
70. Nauta A, Gurtner G, Longaker MT. Wound healing and regenerative strategies. *Oral Dis* 2011; **17**: 541–549.
71. Nemcovsky CE, Artzi Z. Comparative study of buccal dehiscence defects in immediate, delayed, and late maxillary implant placement with collagen membranes: clinical healing between placement and second-stage surgery. *J Periodontol* 2002; **73**: 754–761.
72. Osburn RC. Preservation of the alveolar ridge: a simplified technique for retaining teeth beneath removable appliances. *J Indiana State Dent Assoc* 1974; **53**: 8–11.
73. Paolantonio M, Dolci M, Scarano A, d'Archivio D, di Placido G, Tumini V, Piattelli A. Immediate implantation in fresh extraction sockets: an controlled clinical and histological study in man. *J Periodontol* 2001; **72**: 1560–1571.
74. Qahash M, Susin C, Polimeni G, Hall J, Wikesjo UM. Bone healing dynamics at buccal peri-implant sites. *Clin Oral Implants Res* 2008; **19**: 166–172.
75. Roe P, Kan JY, Rungcharassaeng K, Caruso JM, Zimmerman G, Mesquida J. Horizontal and vertical dimensional changes of peri-implant facial bone following immediate placement and provisionalization of maxillary anterior single implants: a 1-year cone beam computed tomography study. *Int J Oral Maxillofac Implants* 2012; **27**: 393–400.
76. Sanz I, Garcia-Gargallo M, Herrera D, Martin C, Figuero E, Sanz M. Surgical protocols for early implant placement in post-extraction sockets: a systematic review. *Clin Oral Implants Res* 2012; **23** (Suppl. 5): 67–79.
77. Schenk RK, Buser D, Hardwick WR, Dahlin C. Healing pattern of bone regeneration in membrane-protected defects: a histologic study in the canine mandible. *Int J Oral Maxillofac Implants* 1994; **9**: 13–29.
78. Schneider D, Weber FE, Grunder U, Andreoni C, Burkhardt R, Jung RE. A randomized controlled clinical multicenter trial comparing the clinical and histological performance of a new, modified polylactide-co-glycolide acid membrane to an expanded polytetrafluorethylene membrane in guided bone regeneration procedures. *Clin Oral Implants Res* 2014; **25**: 150–158.
79. Schroeder HE. The periodontium. In: Oksche A, Vollrath L, editors. *Handbook of Microscopic Anatomy*. Berlin: Springer, 1986: 233–246.
80. Schropp L, Wenzel A, Kostopoulos L, Karring T. Bone healing and soft tissue contour changes following single-tooth extraction: a clinical and radiographic 12-month prospective study. *Int J Periodontics Restorative Dent* 2003; **23**: 313–323.
81. Schwarz F, Wieland M, Schwartz Z, Zhao G, Rupp F, Geisgerstorfer J, Schedle A, Broggin N, Bornstein MM, Buser D, Ferguson SJ, Becker J, Boyan BD, Cochran DL. Potential of chemically modified hydrophilic surface characteristics to support tissue integration of titanium dental implants. *J Biomed Mater Res B Appl Biomater* 2009; **88**: 544–557.
82. Sculean A, Gruber R, Bosshardt DD. Soft tissue wound healing around teeth and dental implants. *J Clin Periodontol* 2014; **41** (Suppl. 15): S6–S22.

83. Sharma S, Thakur SL, Joshi SK, Kulkarni SS. Measurement of gingival thickness using digital vernier caliper and ultrasonographic method: a comparative study. *J Investig Clin Dent* 2014; **5**: 138–143.
84. Szpaderska AM, Walsh CG, Steinberg MJ, DiPietro LA. Distinct patterns of angiogenesis in oral and skin wounds. *J Dent Res* 2005; **84**: 309–314.
85. Szpaderska AM, Zuckerman JD, DiPietro LA. Differential injury responses in oral mucosal and cutaneous wounds. *J Dent Res* 2003; **82**: 621–626.
86. Ten Heggeler JM, Slot DE, Van der Weijden GA. Effect of socket preservation therapies following tooth extraction in non-molar regions in humans: a systematic review. *Clin Oral Implants Res* 2011; **22**: 779–788.
87. Thoma DS, Muhlemann S, Jung RE. Critical soft-tissue dimensions with dental implants and treatment concepts. *Periodontol 2000* 2014; **66**: 106–118.
88. Trombelli L, Farina R, Marzola A, Bozzi L, Liljenberg B, Lindhe J. Modeling and remodeling of human extraction sockets. *J Clin Periodontol* 2008; **35**: 630–639.
89. Vera C, De Kok IJ, Reinhold D, Limpiphipatanakorn P, Yap AK, Tyndall D, Cooper LF. Evaluation of buccal alveolar bone dimension of maxillary anterior and premolar teeth: a cone beam computed tomography investigation. *Int J Oral Maxillofac Implants* 2012; **27**: 1514–1519.
90. Vercellotti T. Piezoelectric surgery in implantology: a case report – a new piezoelectric ridge expansion technique. *Int J Periodontics Restorative Dent* 2000; **20**: 358–365.
91. Vervaeke S, Dierens M, Besseler J, De Bruyn H. The influence of initial soft tissue thickness on peri-implant bone remodeling. *Clin Implant Dent Relat Res* 2014; **16**: 238–247.
92. Vignoletti F, Johansson C, Albrektsson T, De Sanctis M, San Roman F, Sanz M. Early healing of implants placed into fresh extraction sockets: an experimental study in the beagle dog. De novo bone formation. *J Clin Periodontol* 2009; **36**: 265–277.
93. Vignoletti F, Matesanz P, Rodrigo D, Figuero E, Martin C, Sanz M. Surgical protocols for ridge preservation after tooth extraction. A systematic review. *Clin Oral Implants Res* 2012; **23** (Suppl. 5): 22–38.
94. Vignoletti F, Sanz M. Immediate implants at fresh extraction sockets: from myth to reality. *Periodontol 2000* 2014; **66**: 132–152.
95. Wang RE, Lang NP. Ridge preservation after tooth extraction. *Clin Oral Implants Res* 2012; **23** (Suppl. 6): 147–156.
96. Wennerberg A, Albrektsson T. Effects of titanium surface topography on bone integration: a systematic review. *Clin Oral Implants Res* 2009; **20** (Suppl. 4): 172–184.
97. Wood DL, Hoag PM, Donnenfeld OW, Rosenfeld LD. Alveolar crest reduction following full and partial thickness flaps. *J Periodontol* 1972; **43**: 141–144.
98. Zitzmann NU, Scharer P, Marinello CP. Factors influencing the success of GBR. Smoking, timing of implant placement, implant location, bone quality and provisional restoration. *J Clin Periodontol* 1999; **26**: 673–682.
99. Zweers J, Thomas RZ, Slot DE, Weisgold AS, Van der Weijden FG. Characteristics of periodontal biotype, its dimensions, associations and prevalence: a systematic review. *J Clin Periodontol* 2014; **41**: 958–971.