The Partial Extraction Therapies: Root-mediated Ridge Preservation in Restorative & Implant Dentistry

by

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"Roots without crowns, embedded or otherwise, have historically been the abomination of every dentist. Since most extracted teeth have undergone pathologic pulpal changes, the residual root fragments could be a source of future pathology. These root fragments when observed on postoperative radiographs are considered unesthetic by the operator and reflect bad form when seen by others. The stigma associated with such a professional procedure has unnecessarily delayed research on retaining root stumps"

~ G.S. Poe et al, 1971

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LIST OF ABBREVIATIONS

3D – 3-dimensional

BB – bundle bone

CBCT – cone beam computed tomography

CTG – connective tissue graft

dPTFE – dense polytetrafluoroethylene

EMD – enamel matrix derivative

FGG – free gingival graft

FPD – fixed partial denture

GBR – guided bone regeneration

IIP – immediate implant placement

IIPP – immediate implant placement and provisionalization

MRR – molar root resection

PDL – periodontal ligament

PET – partial extraction therapy/therapies

PRF – platelet-rich fibrin

PS – pontic shield

PST – pontic-shield technique

RCT – randomized trial/randomized control trial

RPD – removable partial denture

RST – root submergence technique

SR – systematic review

SS – socket shield

SST – socket-shield technique

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I. INTRODUCTION

As early as the 1950s, 1960s, face and alveolar ridge changes as a result of tooth loss were documented, classified, and reported (1-3). This challenge persists today, seen as atrophy at edentulous sites, recession following immediate implant placement (IIP), tissue loss that typically requires augmentations or alternative solutions (4). Preventative measures to offset this loss also date back several decades, with the earliest socket grafting procedures in the mid 1970's (5). The same period saw the first bone augmentations of the atrophic edentulous mandible (6). In the 1990's the first cases of guided bone regeneration (GBR) adjacent to dental implants was reported (7), and the GBR era thereafter took off as commercial biomaterials gained popularity (8). And while GBR by bone substitute material and membrane is likely the most widely used treatment for ridge defects today, preventative measures utilizing the patient's own tooth root to minimize ridge loss are far less popular as represented by far fewer reports in the literature (9). Tooth root-mediated ridge preservation dates back to before GBR was first reported (10). The 1970's already had 10-year data on root-resection to encourage molar retention in lieu of full extraction (11). Today authors have reported phenomenal results at 20 and 30-year follow-up (12). Three decades later, two landmark reports took the next step to apply this root-mediated ridge preservation to implant dentistry. In one report an incisor root was submerged in a child to encourage replacement resorption for later implant placement (13). In the other landmark report roots were submerged beneath implant-supported fixed partial dentures (FPD) (14). The sum of these events led to the first report of the socket-shield technique (SST) at IIP by Hürzeler & co-workers (15). The concept progressed from submerging a whole root, to sectioning a root with its facial portion remaining adjacent to an immediate implant.

SST together with root submergence technique (RST), pontic shield technique (PST), Glocker technique (AKA delayed socket shield) and molar root resection (MRR), are evidence-based treatments that utilize the patient's own tooth root to preserve alveolar ridge tissue – collectively known as the partial extraction therapies (PET) (4, 16). 40 or more years have passed since the first reports of MRR and RST. 10 years have passed since the first SST report. The current available literature on the SST includes randomized trials, human histology, animal histology, patient cohorts greater than 100 participants, modified technique reports, numerous case reports, with a majority contribution by the author of this thesis. A comprehensive timeline of these developments is provided in the supporting information (Fig. S1). The works reported hereafter intend to demonstrate that the PET are a viable alternative to the extract-and-augment approach.

II. BACKGROUND

II.1 Clinical and histological post-extraction changes

II.1.1 Clinical data

Tooth loss leads to loss of alveolar ridge dimension (3, 17, 18). This loss can vary. Authors have attempted measuring this loss on study casts prepared at extraction compared to after healing. In 46 patients assessed, there was an average of 50 % horizontal ridge reduction (19). Most of the change occurred during the first 3 months, more so at molar sites, and more in the mandible. The methodology however (and that of many other similar studies) is debatably unacceptable. Dimensional change measured on study casts is not the most accurate, and provides no information of the underlying bone change. Neither can ridge callipers measure ridge width at a consistently reproducible position. Other studies have reported archaic analogue methods of measuring changes with a periodontal probe (20).

II.1.2 Histological and radiographic data

Histology and/or 3-dimensional (3D) cone beam computed tomography (CBCT) are debatably the only valid tools of measurement to assess these post-extraction alveolar bone changes. In one of the most widely cited studies, the principle findings in the dog model were that the alveolar socket crest comprised almost solely of bundle bone (BB) (17). The current author's research confirmed this. At maxillary anterior teeth, the facial crest in 83-92 % of patients is ≤1 mm, thus comprising solely of BB (Fig. S2, Table S1) (21). BB has been confirmed to resorbed during phase 1 of socket healing (17). Most of this loss, and thus vertical reduction, occurred in the initial 8 weeks after extraction. Phase 2 of socket healing resulted in later, additional, outer alveolar ridge resorption. The reasons for this remain unknown. Histological data of ridge alterations is however near impossible to study in humans. Thus, 3D radiography is then the only reliable assessment of alveolar bone change, and such studies are exceedingly rare (22). By comparison, there are innumerable studies reporting on socket grafting (18). To retrieve data from the literature on the extent of dimension loss following tooth extraction, some clues may be found in these ridge preservation studies that included a control arm. To identify by how much the extraction socket may resorb, a careful dissection of a recent meta-analysis provided such measurements. After all, meta-analysis is regarded the "highest level of evidence" (debated in section V.1.2). To quote from the article: "the results of a pooled quantitative analysis revealed that alveolar ridge preservation (ARP) via socket grafting (ARP-SG), as compared to tooth extraction alone, prevents horizontal (M = 1.99 mm; 95% CI 1.54–2.44), vertical mid-buccal (M = 1.72 mm; 95% CI 0.96–2.48) bone resorption". What is actually being reported is that the weighted mean difference (WMD) between the changes resulting from no treatment versus socket grafting are 1.99 mm horizontal and 1.72 mm vertical. Data is not directly reported on how much extraction sockets resorb without any treatment in humans. This meta-analysis processed results from 25 publications involving randomized control trials (RCT). Of these, as argued above, only 6 reported on CBCT measurements. To dissect the data further, scrutiny of those 6 full text publications noted the following:

- 2 RCTs measured CBCT images that were unclear and hazy (Figs. S3, S4) (23, 24). It remains uncertain how linear measurements of any accuracy were obtained.
- 1 study measured healed, grafted sockets, at the coronal, mid, and apical areas. The averages were 6.1, 3.1, 5.7 mm respectively (23). Such a healing ridge morphology seems impossible (Fig. S5).
- In some studies, only vertical changes were measured. Also, the images provided did not have the ridge and vestibular mucosa separated, further reducing visibility and reducing measurement accuracy. Worse, 1 study provided no example CBCT images at all (25). Others studies had clear and appropriate CBCT images (26).
- Some studies reported on sockets with completely missing buccal bone (24). How then could same be meta-analysed with same, to coherently and accurately pool data of the same kind?
- Some studies were strict in keeping to assessing single extraction sites within the same jaw and same tooth type only (27). Other studies included heterogenous sites and criteria, and even multiple random adjacent extractions (28). Some authors neglected to report on these inclusion criteria altogether (25).
- One study had exemplary selection criteria. Any site that had residual bone crests positioned >3 mm from the cemento-enamel junction (CEJ) was rejected. Thus only fully intact sockets included (27). Though, horizontal bone measurements were omitted.

Disregarding studies that do not represent the bone loss incurred at intact sockets, and others with questionable study design, inclusion criteria, etc., the individual measurements for several CBCT studies are presented in Table 1. How much bone resorption can then be expected in humans when a tooth is removed? The most appropriate aggregation of results appears to show that at non-molar tooth sites, approximately 3 mm of horizontal bone change can be expected at 3 months (23, 25, 26).

Table 1: Literature results on amount of post-extraction socket change

Authors	Timing of postoperative CBCT scan	Bone measurement level	Horizontal loss	Vertical loss	Number of sites (in control group of RCT)	Jaw(s) studied	Tooth extraction sites	Single or multiple extractions
Araujo et al, 2015	4 months	NA	No data	- 3.6 mm	14	Both	Premolars to anterior teeth	Single
Temmerman et al, 2016	3 months	1 mm below crest 3 mm below crest 5 mm below crest	- 3.3 mm - 1.0 mm - 0.5 mm	- 1.6 mm	11	Both	Premolars to anterior teeth	Single
Jung et al, 2013	6 months	1 mm below crest 3 mm below crest 5 mm below crest	- 3.3 mm - 1.7 mm - 0.8 mm	- 0.5 mm	10	Both	Premolars to anterior teeth	Single
Karaca et al, 2015	3 months	NA	- 1.22 mm	- 1.03 mm	10	Both	Any	Multiple
Pang et al, 2014	3 months 6 months	NA	- 2.72 mm - 3.56 mm	- 2.12 mm - 3.26 mm	15	Both	Not disclosed	Single
Chappuis et al, 2013	2 months	At bone crest	-0.8 mm	-7.5 mm	39	Maxilla	Canines/incisors	Single

* The authors reported these positive values, assumed as horizontal gains

Some populations at early healing incur less horizontal bone loss of only about 1 mm (22, 28). However additional horizontal bone loss may occur from months 2-6 (22, 23, 25). Vertical bone changes are however more variable than horizontal. Some data shows as little as 0.5 mm at 6 months, and as much as 7.5 mm at 2 months (Table 1). Thus, to accept at face value the pooled data of meta-analyses is often a great error. Some authors have similarly questioned the data with regards alveolar ridge change (29). What cannot be disputed though is that alveolar bone is lost when a tooth is removed.

II.2 Mitigating post-extraction changes: Post-resorption measures

II.2.1 Hard tissue augmentation techniques

A comprehensive review of all augmentation techniques and materials and their features is beyond the scope of this discussion. These have been addressed in the current author's textbook chapter (30). In brief, alveolar bone defects can be augmented by an enormous variety of techniques. Surely the most widely utilized is GBR, typically by commercial bone material secured with a membrane. The concept and technique date back to the early 1990's and have been extensively researched since (7). Each technique and material, be it bone or membrane or fixation method, has its own pros and cons. The pros include abundant research data, decades of worldwide use, immediate availability, generally positive biocompatibility, ability to partially repair lost bone tissue, to replace lost volume, etc. Cons include high cost, technique difficulty, risk, only partial bone repair possible, with complications, morbidity, treatment delay, and variable results, etc (31). Autogenous bone harvest and oral grafting techniques each also have their positives and negatives, often opposite to commercial GBR material techniques. Autogenous bone may be the closest to ideal, a gold standard, but there is no single best evidence-based treatment among all these techniques for all clinical situations (32). Newer materials have emerged as others have evolved. The platelet aggregates (PRF, L-PRF, A-PRF, etc.) contribute cells, factors, fibrin mesh, and improve soft tissue healing, GBR handling properties, etc. The current author's research proved by human histology that PRF has no proven benefit for bone healing though (Figs. S6, S7) (31, 33). Tooth dentin autogenous graft has had promising data with evidence of bone integration (34). The Khoury split bone block graft has become more widely known and utilized (35). Overall these treatments afford patients possibilities to regain some lost alveolar ridge tissue. They however remain curative rather than preventative.

II.2.2 Soft tissue augmentation techniques

Tooth loss and resorption of alveolar bone also results in soft tissue changes (36). The width of attached keratinized mucosa (AKM) is often reduced. The vestibular depth may also diminish. These are soft tissue features not ideally compatible with restorative prosthetic treatment. To repair a ridge defect may, additional to bone augmentation, require soft tissue surgery and augmentation to re-establish vestibular depth, adequate AKM width, and soft tissue thickness. Commonly used techniques harvest a connective tissue graft (CTG) or free gingival graft (FGG) from the palate. The current author published a minimally invasive exposure technique specific for this purpose at esthetic sites (37). Commercial allograft materials are a viable alternative to CTG, but at increased cost (38). Combined, the pros include the ability to partially repair lost soft tissue, to increase volume and desired quality, improve function and esthetics. Cons may include technique difficulty, morbidity, risk, etc. The current author also published on adverse, hyperplastic, keloid-type healing after augmenting anterior esthetic sites in patients with CTG (Fig. S8) (39).

II.2.3 Prosthetic correction techniques

Prosthetic solutions may supplement surgical correction of a ridge defect, or replace a surgical option altogether (40). Restorative materials substitute for the tooth crown(s) and ridge loss. These may be more necessary at multiple missing tooth sites and ridge defects with greater resorption. The advantages would include obviating the risks and morbidity of extensive augmentation surgery. The disadvantages may include significant cost, and often less than ideal, artificial esthetics. That said, not all alveolar ridge defects necessitate extensive surgery to repair and may be successfully treated by prosthetics alone.

II.3 Mitigating post-extraction changes: Preventative measures

II.3.1 Low trauma tooth extraction

Excessive surgical trauma to the extraction socket, particularly the fracture of its socket walls, may exacerbate ridge loss. Low trauma tooth extraction utilizes additional treatment steps and instrumentation instead of extraction forceps alone (41). Micro-periotomes are used to sever the PDL. The tooth is decoronated, sectioned into pieces, and these removed incrementally. Greatest care is taken not to fracture the buccal/facial bone plate (Fig. S9).

II.3.2 Ridge preservation by socket grafting

As early as the 1960's and 1970's, clinicians were already aware of the post-extraction resorption dilemma, and were experimenting by grafting sockets with acrylic resin, plaster of paris, autogenous costo-chongral cartilage, hydroxylapatite, etc. (1, 5). Today, literally thousands of publications have reported on innumerable combinations of materials, typically commercial biomaterials, for this purpose (18). Some researchers have dedicated years of work to popularizing these techniques and elucidating protocols for best outcomes (42, 43). The topic is truly complex. Some ridge loss may be circumvented by this treatment (18, 44). It is the current author's opinion that in a patient losing a secondary tooth at a young age, that grafting of a socket with a non-resorbing bone substitute may be beneficial (Fig. S10). Such a patient would only have implant therapy years later. Conversely, an adult patient planned for implant therapy (less than a year later) should not have a socket graft with a such a material. Consider the meta-analysed data discussed in section II.2. Authors Avila-Ortiz et al reported "alveolar ridge preservation (ARP) via socket grafting (ARP-SG) prevents horizontal bone resorption (M = 1.99 mm) (18). Worded differently, on average, when all data from RCTs are combined, a dentist can expect an extraction socket to lose about 2 mm more in width than sockets that are grafted. The statement is problematic for numerous reasons. It is unclear whether these dimensions refer to alveolar bone loss/preservation, or soft tissue loss/preservation, or a combination. How then can one apply this data clinically to make decisions whether or not to graft sockets in lieu of later augmentations? Assume for a moment this 2 mm horizontal loss prevention refers solely to alveolar bone. The current author's research measured the horizontal width of 100 maxillary central incisor tooth sites (Fig. S11) (45). The mean horizontal width from facial bone crest to palatal bone crest was 7.68 mm. To illustrate this point the aforementioned values can be rounded off to the nearest whole number. Analysis of the data for horizontal bone change in section II.2

concluded approximately 3 mm is lost at non-grafted sockets. Thus, if 2 mm loss was prevented on average, grafted sockets still lose 1 mm. If an implant (3.5 – 4 mm diameter) is planned for a maxillary central incisor site, the ridge needs to be 7 mm wide at minimum. These basic calculations made from the study's CBCT data suggest that in most cases even after ridge preservation, a second augmentation would be necessary.

II.3.3 Prosthetic pontic support

As stated, tooth loss leads to soft tissue loss. Papillae reduce in height, gingival contours no longer symmetric, overall volume of the site reduces as the soft tissue collapses (46). A pontic tooth inserted into the extraction site mechanically supports the soft tissue at the socket entrance – the gingival margin, interdental papillae – whilst simultaneously stabilizing the blood clot in the socket beneath it (Fig. S12). A case series by Tarnow and coworkers reported a reduction of about 1 mm horizontally and 1.5 mm vertically when an ovate pontic is inserted at an extraction socket (29). Some loss nonetheless can be expected.

II.3.4 Immediate implant placement: the dual-zone therapeutic concept

By current definition, immediate implant placement (IIP) is an implant placed in the socket on the same day as tooth extraction. For the purpose of supporting the extraction socket soft tissues, immediate implant placement and provizionalization (IIPP) refers to additionally restoring the implant with a provisional restoration. A customized healing abutment similarly supports these tissues. In this way a symmetric gingival margin, papillae height and fill, etc. may be preserved (47). An immediate restoration is thus provided to the patient. This may be compared to the alternative of extraction, a period of healing and tissue resorption, followed by re-entry surgery, implant placement (early or late; types 2 or 3), with tissue augmentations to compensate for the loss, followed by a period of prosthetic development of the soft tissue (48). The advantages of IIPP thus may include a reduced number of surgeries, lower morbidity, less commercial biomaterials required, etc. Disadvantages of IIPP relate to the risk of incorrect case selection that may lead to biological and esthetic failure, as well as the skill required to provide these. The International Team for Implantology (ITI) consensus statements are at times revised. These in 2009, 2014, emphasized IIP to have significant risks and with no added advantage over early placement (49). The years of evidence thereafter however could not support these statements in the 2018 ITI consensus statements (48). IIP (type 1) out-performed early and delayed placements (types 2 and 3) in terms of survival. Early placement (type 2) lacked "sufficient clinical documentation" to support all possible loading protocols. To mitigate the risks previously emphasized by the ITI consensus statements, mainly attributed to recession at the midfacial mucosa, authors favouring IIPP have developed strict protocols (Tables S2, S3). Chu et al combined several techniques into the contemporary dual-zone therapeutic concept (50). These include low-trauma tooth extraction, apico-lingual implant positioning away from the facial/buccal bone plate, grafting of the buccal gap (at both bone and tissue zones), and immediate screw-retained provisional restoration. Later, other working groups emphasized facial and smile diagnosis, CBCT planning, prosthetic knowledge to both develop and transfer submergence contour, and additional augmentation of the facial soft tissue with CTG (47).

III. STATEMENT OF THE PROBLEM

1. Post-extraction resorption of the alveolar ridge is a challenge to both the patient and clinician. Interventions to surgically augment the loss have inherent disadvantages. These attempts are curative, not preventative.

2. Ridge preservation by socket grafting is also wholly inadequate. Despite the cost, time, technique required, resorption will still occur.

3. The "extract-and-augment" mindset is widely prevalent. This is driven by an industry of commercially manufactured biomaterials. Challenging this convention is met with much resistance, when conventional extraction of teeth with pathology is regarded as choice therapy.

4. To demand that overwhelming evidence validate PET is a contradiction. All other regenerative therapies (namely GBR) were for long practiced without prospective studies, without RCT, or patient cohorts of >100, etc.

5. Much has not been known about the PET. For example, what tissues histologically heal in these areas? What is the fate of the implant and how does this data compare to conventional therapy? Do the PET achieve ridge preservation and how do these compare to other ridge preservation approaches? What are the preferences of clinicians with regards to these treatments and why? If there are concerns of complications, what are these complications, why do they occur, and how can they better be prevented? Overall, how can the PET be improved, be didactally taught to clinicians, to improve treatment outcomes for patients?

AIMS

To challenge "conventional wisdom" and convincingly demonstrate that the intentional retention of a root or a remnant thereof are valid treatment options and a benefit to the patient.

IV. METHODOLOGY

Retrospective studies

A retrospective study of 128 patients that received SST was carried out (51). Clinical and radiographic parameters were assessed at up to 4-years follow-up. Implant survival was the primary objective measure reported.

Technical reports

The term partial extraction therapies (PET) was coined in 2016, when the collective concept of treatments utilizing the patient's own tooth root for ridge preservation was published in part 1 of a technique report (4). Part 2 published detailed technical aspects of PET in a second technique article (16). The same period saw publication of the pontic-shield technique (52). Thereafter, the results from the retrospective study were addressed in a prosthetic management technical report to circumvent the most common complication of internal socket shield (SS) exposure (53). Thereafter also, a second technical report described how to treat immediate molar implant sites with SST (54). Ten years of accumulated experience were applied to an updated and revised step-by-step PET protocol for carrying out the SST (55). A technique report additionally describes the esthetic tunnel exposure technique for submerged implants in the esthetic zone (37).

Also, two technique reports describe step-by-step how to carry out the root submergence technique at a) single to short-span edentulous sites, and b) long-span to fully edentulous jaws (56, 57).

Histological study in animals

A cross-sectional observation study was carried out in 8 beagle dogs to simulate the SST at IIP (58). The aim was to observe by histological examination the outcomes at variable preparations of the SS.

Histological studies in humans

A cross-sectional observation study was carried out on the extraction of an upper premolar implant with its adjacent root portion against the implant and surrounding bone (59). The aim was to observe the healed tissues at the implant in a human.

In an earlier study, the aim was to investigate the value of PRF as a biomaterial to stimulate alveolar bone healing (31). A split-mouth, prospective study was designed. 8 human bone biopsy samples were compared by histological examination.

In another study, the complication of hyperplastic response resulting from CTG and augmentation in the esthetic zone (39). Gingival biopsy was obtained from 3 such patients and observed by histological examination.

Web-based questionnaire study

An online questionnaire study was carried out, inquiring into the preference of clinicians between socket grafting for ridge preservation or root submergence technique (RST) (60). Dentists and dental specialists internationally were invited to volunteer information via a web-based questionnaire.

Pre-clinical cadaver study

A pre-clinical, analytic, human cadaver study was carried out. A digitally guided approach to preparing the SS was tested in 10 cadaver jaws, 17 sites total (61). The accuracy of the SS planning and the technique were assessed by comparing pre-operative micro-CT scans of the jaws to post-operative scans.

Radiographic studies

In a cross-sectional observation study, 591 maxillary anterior tooth sites in 150 patients was assessed on CBCT (21). The tooth root positioning was classified by axial orientation. The alveolar bone and facial bone plate was measured.

In a second cross-sectional observation study, 100 maxillary anterior tooth sites in 84 patients were also assessed on CBCT (45). The pre-extraction socket dimensions were determined, by measuring from facial bone crest to palatal.

Evidence review

A comprehensive review with a focus on a critical appraisal of the data reported, was carried out on the root submergence technique (RST) (9). Chapters were also published in two textbooks, each on the use of materials to augment alveolar defects (30, 33).

V. RESULTS. DATA ON THE PARTIAL EXTRACTION THERAPIES

V.1 The root submergence technique

V.1.1 Historic evidence and origins of the technique

Dating all the way back to the 1960's, submerging roots for preservation of the alveolar ridge was the first PET (10). This evolved from the overlay/overdenture technique, but with the tooth decoronated and covered beneath oral mucosa. The rationale was to protect abutment teeth susceptible to dental caries and periodontal disease (62). By submerging the root, its attachment apparatus supporting BB, the root free of pathology, the ridge could be preserved. The indications are numerous. Originally intended for full dentures, RST also maintains ridge volume and esthetics also pontic sites, at FPD (both tooth and implant-supported) (14, 63). Histological studies confirm that little vertical change occurs post-extraction at approximal bone peaks supported by adjacent teeth (64). Thus, RST is of greatest benefit to preserve ridge tissues adjacent/between multiple implants (4, 14).

This PET however is today somewhat of a forgotten technique in the literature. Also, too few RCT on RST have been reported to conduct a formal systematic review (SR) thereof (65, 66). Such reviews, especially if meta-analyzed, are generally considered the highest level of evidence (67). However, despite alleged strict selection criteria for data inclusion, all too often these SR aggregate numerous heterogenous data that grossly skew the results. For example, Hsu et al 2017 carried out a meta-analysis on the effect of platform switching, and combined data from unstable external connection implants with mis-matched abutments, to data from morse-taper-like connections with inherent platform switching (68). Other SR conversely are incredibly consistent, to a fault. The 2018 Osteology Foundation Consensus report on lateral bone augmentation was based on one such SR and meta-analysis (69). The SR by authors Sanz-Sanchez et al, 2017, included 8 RCTs, all comparing GBR with GBR to conclude that GBR is effective (70).

V.1.2 Counter-argument & evidence: Systematic review of root submergence

The current author conducted the most comprehensive review on RST ever carried out (9). The PICO format (Population, Intervention, Comparison and Outcomes) and PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) govern accurate conformity of SR (71, 72). Since too few studies/trials on RST exist, and in lieu of a SR that lumps data together, a concise review of all the literature published on RST was carried out, with critical appraisal of the data reported. In part, the PICO question as per Needleman and co-workers could be addressed and structured the methodology of the review (71). Also in keeping with SR convention, the established PRISMA guidelines were observed wherever possible (72).

PICO question

What are the outcomes of the different methods to submerge tooth roots? **Population:** Studies investigating root submergence in either animal and human subjects. **Intervention:** RST investigated in this review is defined as

"the intentional partial extraction of a tooth, such that a portion of the root remains in-situ within its alveolus, free of disease and fully submerged beneath healed mucosa, for the purpose of ridge preservation". This generally requires the cutting off the tooth crown (decoronation), with or without additional corono-apical reduction of the tooth root. The root may be vital, or endodontic treatment may be carried out (10, 73). **Comparison:** Too few studies of RST exist with a control group (65, 66). Thus the inclusion criterion for solely selecting RCT has been wavered for this review. **Outcomes of interest:** Primary outcome (i) Ridge preservation achieved. Secondary outcomes (ii) Positive outcomes reported: mucosal coverage maintained, radiographic evidence of coronal bridging (coronal bone/hard tissue healing over root), histologic evidence of coronal bridging (coronal bone/hard tissue healing over root). (iii) Adverse healing outcomes reported: root exposure, root exfoliation, infection, alveolar bone loss, loss of vestibular depth, pain & discomfort, root resorption*, need for additional interventions (endodontic treatment, repeat submergence, extraction, etc.)

* Root resorption may not be an "adverse healing outcome". Replacement resorption of a root portion in PET by bone deposition is justifiably a positive outcome. This should be noted, regardless if authors 4-5 decades prior have reported this to be an adverse healing outcome.

Article eligibility criteria

(i) Conventionally RCT are the preference of SR. However, only 2 studies ever have met this criterion. Thus, all studies reporting on the submergence of tooth roots for ridge preservation were screened for this review. Data from both animal and human subjects studies were analyzed. Histological, radiographic, and clinical data were all considered. No prescription was determined for a minimum follow-up period. (ii) Roots submerged as a result of trauma comprise a majority of the RST literature (74). Trauma with alveolar and root fracture may confound the results. All such studies were excluded from this review. (ii) Studies reporting on mandibular third molar roots submerged to prevent inferior alveolar nerve injury (coronectomy/partial odontectomy) were also too heterogenous from the general pool of RST for ridge preservation data (75). These too were excluded. (iii) Numerous studies have investigated submerged roots associated with infrabony periodontal defects, for the purpose of experimental periodontal regeneration. Valuable data could be derived from these studies. Cook et al 1977 submerged 12 roots, noting the ridge preservation potential, and not all roots had periodontal defects (76). However, heterogeneity in technique led to exposure in other studies, which would confound the current review's results (77). Thus, these studies were also omitted from the review. (iv) All methods of tooth decoronation, flap management, and endodontic management (both vital and endodontic-treated roots) were included. (v) Studies published at any date were included. Archived historic data was considered only if the full text article could be analyzed. (vi) Only studies published in English were considered.

Search strategy

Data searches were carried out in the National Library of Medicine (MEDLINE—PubMed), Scopus, and Cochrane databases. The medical subject headings (MeSH) terms searched and their respective results were: "submergence + root" = 498 results; "submerged + root" = 691 results; "submerged + tooth + root" = 125

results; “retained + tooth + root” = 1684 results; “vital + retained + root” = 59 results; “root + bank” = 667 results; “root + retention” = 2984; “partial + odontectomy” = 16 results; “tooth + coronectomy” = 126 results; “tooth + root + coronectomy” = 71 results; “decoronation” = 542 results; “root + ridge + preservation” = 135 results; “submucosal + roots” = 28 results; “submerged + over + denture” = 66 results; “submucosal + over + denture” = 17 results. The MeSH terms “overdenture” and “overlay + denture” combined produced 8445 search results, were far too heterogenous, reporting on implant-supported overdentures, on root-retained overdenture abutments. As stated, these with other search terms not complying with the selection criteria were omitted.

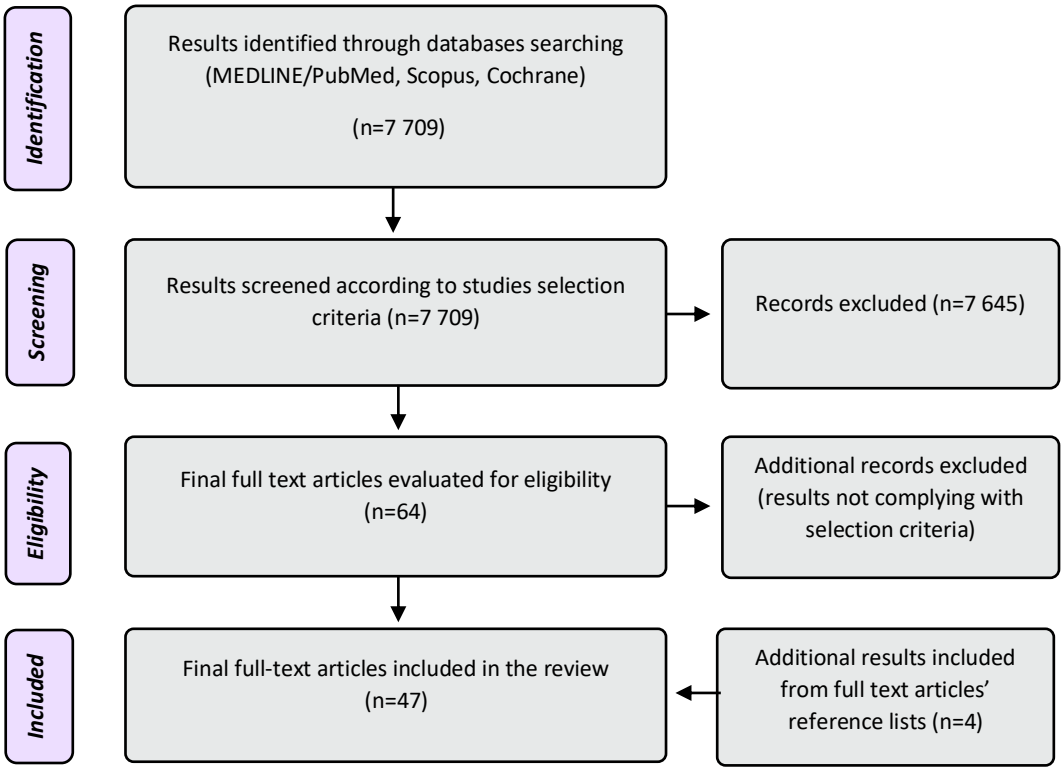


Figure 1. Search strategy of the RST systematic review

Results

The electronic searches of the combinations of terms produced a total of 7 709 results. Each result was screened – both its title and abstract. After applying the selection criteria, excluding non-applicable results, and additionally reviewing all the selected full-text articles’ reference lists, eventually 47 full-text articles were selected for detailed analysis. Of these, 10 studies were conducted in animals, 37 in humans (Figure. 1).

258 roots in total were studied in 34 dogs and 7 monkeys, across 10 animal studies from 1971 to 1984 (Table S4) (78-87). Histological examination was performed in all. Among the vital submerged roots (24 + (6/8) + 24 + 12 roots), 66/68 roots maintained their vitality (79, 84, 85, 87). That is, in the 4 studies submerging vital roots, 97 % of submerged roots maintained their vitality (Fig. S13a). In 2 studies by the same working group examining

92 roots, vitality of root canal tissues was not reported and thus cannot be commented on (80, 81). Coronal bridging (hard tissue – bone, cementum, or secondary dentin healed over of the cut root portion) was reported in 9/10 studies (Figs. S13b, c) (78-83, 86, 87).

Exposure of the root (perforating through the overlying mucosa) was the most commonly reported complication in 7/10 animal studies, 34/258 roots (Table S5). Approximately 86.8 % of all these roots remained submerged. Only 1/10 animal studies did not report complications (85). In all other studies, these ranged from inflammation due to root canal filling material, to abscess and infection, root resorption*, crestal bone resorption, and root migration. 16/258 submerged roots incurred the most serious complications (infection, or roots requiring extraction as a result thereof). Of these, Plata and Kelln, 1976, reported exposure of 1/12 roots that developed a sinus tract (84). O'Neal et al, 1978, reported 3/16 roots developed histological micro-cysts overlying extruded excess root canal filling material (83). Levin et al, 1974, reported cysts/abscess at 3/16 roots (82). Whitaker and Shankle, 1974, reported both vital and endodontically treated roots that became exposed and presented with "severe inflammatory reaction" (9/36 roots total) (87).

475 roots were submerged and reported on in 37 human studies, from 1972 to 2015 (Table S6) (1, 10, 14, 63, 65, 66, 73, 88-113). Most of these studies comprised case series. The majority involved RST beneath removable denture treatment. 5 studies reported on RST at pontic sites beneath tooth-supported FPD (63, 90, 100, 114, 115). 3 studies reported on implant-supported FPD (14, 91, 113). Of the combined human studies, 16 studies reported on vital RST (65, 73, 88, 89, 93-99, 102, 103, 108, 112, 116), 13 reported on endodontic treated roots (1, 10, 63, 66, 90, 91, 100, 104, 107, 109-111, 113-115), and 4 studies reported on both (14, 101, 105, 106, 117). 1 study did not specify (92). Only 2 studies included data from control sites. 1 assessed roots extracted, decoronated, then re-implanted, and the other assessed ridge preservation on panoramic radiographs (65, 66, 92). In 3 studies, histological data was obtained from roots that were elected for extraction subsequent to exposure. These roots displayed varied histological healing. Similar to the results in animal studies, coronal bridging was noted (103). Due to exposure, inflammatory cells were noted in the overlying soft tissue. The root canal tissue was confirmed vital. In another study, inflammatory cells were also noted in the histological examination of 4/8 exposed roots (89). The 3rd histology study reported only root cementum resorption (1).

The primary outcome variable "ridge preservation" was [subjectively] reported in 20 studies (10, 14, 63, 66, 73, 90, 91, 93, 96, 97, 99-101, 105, 109, 111-113, 116). Only 1 study attempted reporting on objective ridge preservation (65). The current author argues that vertical alveolar bone loss evaluated on panoramic radiographs is not an acceptable measurable objective. Radiographic ridge preservation, and/or coronal bridging was reported in 5 studies (1, 65, 89, 103, 110). Root exposure was the most commonly reported complication in 18/37 human studies, 120/475 roots total (25.3 %) (Table S6). Complications ranged from histologic/radiographic root resorption*, to crestal bone resorption, to patient discomfort (under removable dentures), periapical pathology, progressive attachment loss, periodontal abscess, loss of vestibular depth, root migration, and microscopic cysts at extruded endodontic filling material (Table S5). 12/37 studies did not incur

or report complications . In the totalled human studies, the most serious complications (infection, or roots requiring extraction because thereof) occurred in (at least) 18/475 submerged roots. Lam, 1972, reported *"exfoliation* [exposure] *in 4 subjects due to residual infection"* (1). These exposed roots were removed, but their number was not reported. Murray and Adkins 1979 reported 1/8 roots developed a sinus tract (103). Periapical pathology was reported in 4 studies, in 1/9 roots, 4/8 roots , 1/20 roots , and 5/21 roots , with a total complication rate of 2.3 % (89, 101, 106, 110). Stein and Lasnier, 1981, reported a periodontal abscess in 1/3 roots (108). Nagaoka and Okuno 1981 reported progressive periodontal disease in a case of 1 submerged canine root (104). This is contrasted by several reports that conversely treated periodontal defects by submerging roots (117, 118).

A traditional SR was not carried out. The current author has argued that in fact SR of RCTs more often than not fail to critically examine the quality of evidence presented in the original publications. The amalgamation of the data is often highly questionable, and yet still regarded as the "highest level of evidence" (67). Instead, a detailed analysis of all the available data on RST has been presented. These data total 733 teeth in both humans and animals, from single case reports to large studies of 122 submerged roots, from 25 days to 8 years follow-up. It is apparent that the data is steeped in history. In each of the past 5 decades, there have been reports on this PET. However, reporting on the technique has dwindled, whilst placing artificial bone and biomaterials in extraction sockets has grown increasingly popular. An extract-and-augment mindset has become more established, and the conservative preservation of the patient's own tissues slowly phased out. In section V.1.3 results from the survey study may indicate why. In the current SR, the main complication was root exposure. Note that "conventional" GBR/augmentation is not without complication either. Complications in GBR cases using titanium mesh are as much as 21.1 % (119). In a SR of GBR, complication rates ranged 0-45 % (16.8 % average) (118). It should also be noted that the bulk of RST reviewed here (38/47 studies) were carried out prior to 1994 – 26 years ago. Of the combined studies reported post-1994, only 4 roots became exposed, 1 was extracted due to apical pathology, 1 was re-submerged with a soft tissue graft, and 1 site had *"minimal interproximal bone loss"* (Appendix 3). Thus, old technique(s) may have been a factor. Simon first extracted roots, decoronated them outside the mouth, then re-implanted these (66, 107). Gound et al showed a similar technique of extraction and re-implantation in an animal study (78).

Special mention should be made of the exposures following RST, a combined complication rate of 21 % (13.2 % in animal studies, 25 % in human patients). Exposures occurred far more often in patients receiving removable denture treatment. These were attributed to the physical impact of the denture itself – its flange on the healing flap periphery, its fitting surface upon the mucosa (98). Exposures were also more common among "older" studies that utilized inappropriate techniques. In some, patients' crowns were fractured off by mallet and chisel, histologically presenting with microfractures of the root and sharp dentin spicules (Fig. S13d) (87, 106). Also, in several studies roots were decoronated above bone crest (1, 82, 84, 91, 98). Later crestal bone loss may further position roots above the ridge, the mucosa prone to dehiscence. This review recognized that reduction to bone crest, or even preferably below bone crest, may better ensure coronal bridging. This may better ensure longevity of treatment by preventing exposure. Also, the best esthetic outcomes at FPD may be obtained by a soft tissue

graft over the submerged root(s) (14). This may also solve the exposure issue in removable denture patients. Denture flanges may impinge on approximated flaps due to loss of vestibular depth. Moreover, when the flaps are approximated without tension-relieving management, the denture may cause wound dehiscence. This was apparent in several studies that did not make use of any releasing incisions at removable denture treatment (1, 66, 82, 84, 89, 99, 108, 109, 116).

To conclude this SR, as commercial biomaterials became popularized, RST conversely became a less popular technique, evidenced by the volume of literature on each. Nonetheless, literature on RST still provides valuable clinical, radiographic, and histological data of mostly positive healing outcomes. When aiming to preserve the alveolar ridge, especially at pontic sites and adjacent to implants, RST is an established and relevant treatment option. The data in this review indicate reasons why exposure is the most common complication, namely incorrect decoronation, inappropriate soft tissue management, and removable denture treatment. In total, the data reviewed indicates methods to avoid and other methods that would improve treatment outcomes when selecting this PET.

V.1.3 Ridge preservation technique preference: A survey study

Data from the systematic review may explain why reports of the RST have declined in the literature, and why it has possibly become less popular than socket grafting. To further elucidate the preferences of clinicians with regards to these two ridge preservation techniques, an online survey study was carried out. The web-based questionnaire was designed to be as short as possible to attract participation, and comprised three questions only. Question 1 inquired what the respondents' preferred ridge preservation technique is, with options including socket grafting, root submergence, both, neither, and other. Question 2 inquired if the respondents don't submerge roots, why not? The third and last question clarified what the respondents' backgrounds were – dentist, specialist, trainee, etc. The survey was repeatedly shared online across social networks over a period of 1 month.

Results

260 respondents participated in the survey. 17 were excluded from the results. Reasons for exclusion mainly related to conflicting responses (for example: answer to question 1 "Root submergence [is my preferred technique] and answer to question 2 "I don't submerge roots"). Of the 243 included respondents, general dentists comprised the majority (41.2 %). The 2nd and 3rd largest groups were specialist oral surgeons and periodontists (24.7 and 21.8 % respectively). Minor representations were made by other professional backgrounds. No endodontists participated. Socket grafting with a commercial biomaterial was the most popular and preferred ridge preservation technique (43.2 % among all respondents combined). Root submergence was 2nd most preferred (32.9 % of respondents). A minority of respondents either favored both techniques, or favored neither (9.9 and 8.6 % respectively) (Tables S7, S8, S9).

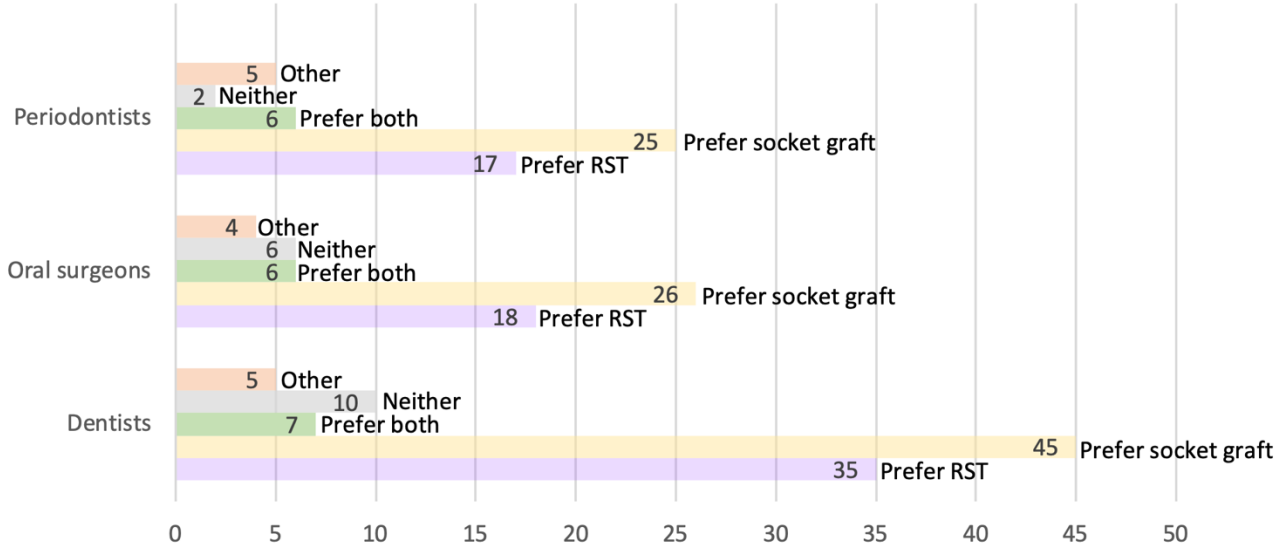


Figure 2: Ridge preservation preferences among the top three most represented groups

Table 2: Responses to question 2 "if you don't submerge roots, why not?"			
Reason	**No.**	**Reason**	**No.**
I prefer conventional extraction	34	I don't do surgery	3
I prefer grafting later if needed	33	I trust socket grafting more than RST	2
Too expensive - cost of endo, root sectioning, surgery	25	Referring dentists don't understand the benefits	1
Too difficult, too much time, too much hassle	22	Lack of research on the technique	1
Complications. I worry about future complications	20	Limitations due to litigation in the UK	1
No undergrad training. Learning curve.	5	Low patient acceptance	1
I prefer immediate implant placement	3		

Among the three largest groups of participants (dentists, oral surgeons, periodontists; 213/243 respondents total) socket grafting was the most preferred ridge preservation (45.1 %) (Fig. 2). Preferences for ridge preservation among these majority groups were highly similar to all the respondents totaled in Tables S7-9. There were no great disparities between either of the three majority professions, and surgical acumen didn't appear to greatly influence preferences.

What can be deduced from this data, limitations aside, is that only about 40% of clinicians would opt for root submergence in a patient to preserve their alveolar ridge (32.9 + 8.9 %). Grafting sockets instead, is slightly preferable to submerging roots. The aim of this study was to learn what clinician's preference for ridge preservation were. 130 respondents answered why RST was not preferred (several clinicians selected more than 1 reason, Table 2). Due to the complications reported in the literature, one would expect this to reflect in clinicians' experience, or concern for the risk. "Complications" is in the top five reasons for not selecting RST, but doesn't appear to be the main motive. When the number of responses are measured against the total respondents who opt not to submerge roots, or who prefer neither RST nor socket grafting, this group appeared accustomed to conventional extraction, then healing with resorption, and grafting later to replace the loss (26 – 27 % of these respondents).

V.1.4 The root submergence technique at single tooth sites to short-span edentulous sites

The systematic review of the RST reported that complications were numerous (9). Chief among these was exposure of the root perforating the overlying mucosa. This complication occurred in 25.3 % of all patients. These also occurred more frequently in "older" studies, at full removable denture treatment, when incorrect techniques were used (1, 66, 103). At FPD, exposures were less frequent. Nonetheless, when these did occur, incorrect technique was the cause (91). Drawing on the successes and failures reported in the literature, this technique report provides the step-by-step root submergence technique at single sites and short edentulous areas.

Technique

The clinician providing the root submergence technique requires an intermediate level of surgical knowledge, training or mentoring, and experience. Comprehensive patient assessment prior to surgery is mandatory. All submerged root sites in the esthetic zone require detailed planning, including the projected prosthetic outcomes initiated by facial and smile analysis and diagnosis (120). The clinician needs to consider all the associated factors with regards to incorporating the pontic site/sites into an ideal smile diagnosis, pink and white esthetics harmonious with the patient's face (121). Projected planning transferred to the patient as a trial restoration or "mock-up" is strongly advised. Next, decisions regarding the tooth considered for root submergence are to be made. All alternative treatment options are to be provided to the patient. If considering RST, compliance with its treatment indications are to be considered (Table S10).

The following steps then detail the clinical procedures to submerge the root(s) and restore the patient:

1. Thoroughly assess and diagnose the tooth, pulp status, and/or existing endodontic treatment (Table S11). Vital and disease-free roots (Fig. 3a) – proceed to step 2.1. If endodontic treatment is required additional to submerging the root, complete this prior to decoronation and surgery. Make every attempt to isolate with rubber dam and clamp, even if crown/coronal structure is lacking. Do not plan to provide endodontic treatment during surgery. A rubber dam cannot by adequately adapted after raising the flap and decoronation to or below bone crest. Moreover, bleeding at a raised mucosal flap compromises moisture control. The surgical site cannot be adequately protected from the endodontic rinse either. Continue to decoronation of the tooth after root canal treatment and sealing is complete. Make an exception if diagnosis of non-vital root canal tissue after decoronation – discussed in step 6. This may require compromised endodontic treatment during of the root submerging procedure.

2. Proceed to step 3 if the tooth crown is absent or mostly absent due to advanced caries, traumatic fracture, dislodged crown restoration etc. If the tooth crown is in position, decoronate the tooth by cutting the crown approximately 2 mm above gingival level (Fig. 3b). Take special care if previously endodontic treated tooth post-and-core and crown, not to fracture the root during removal.

2.1 If the original tooth crown is in position, decoronate the tooth using a high-speed dental handpiece with an

irrigated bur. Several burs may be suitable. Recommended are both carbine and diamond burs with narrow, tapered ends (Fig. 3c). Section the crown from the root, cutting horizontally/mesio-distally. Do this first to a supragingival level, to both avoid damaging the soft tissue, and to allow coronal structure in the event of endodontic treatment need. Take extreme care to also not damage the adjacent tooth crowns. Vestibular retraction for all treatment is recommended.

2.2 Start cutting from the interproximal area if space is sufficient (Fig. 3d). Cut the crown in a horizontal saw-motion toward to the opposite interproximal space. Do not only move in a lateral motion. Cut horizontally while also moving the rotary instrument in a facio-lingual motion. Constant movement prevents the rotary instrument becoming lodged in the tooth. Ensure the cut tooth is well irrigated.

2.3 If there is no interproximal space to fit the rotary instrument, cut first vertically from the mid-incisal/occlusal point, creating a slot through the crown (Fig. 3e). Then cut the crown in a lateral motion as described in step 2.1. Always take care not to damage adjacent tissues. Visualize the bur cutting supragingival on both the facial and lingual aspects. Follow the scallop of the gingiva. Use high volume suction on the lingual, a suction tip with a large orifice, to collect the sectioned crown when dislodged, preventing the patient from aspirating fragments. Provide additional protection against aspiration by draping gauze over the back of the mouth.

2.4 If the tooth has a bonded post that is assessed as sound, the endodontic treatment and root health also adequate, cut the crown with post-and-core may as described in steps 2.1 and 2.2 (example from different case, Fig. 3f). Assess the remaining post within the sectioned root. Remove the post if it is mobile. If secure, if no need for further endodontic treatment, leave the remaining post in the root.

3. Make an intrasulcular incision circumferential at the coronal root with a size 15c blade or similar. Cut and sever the mid-papillae (Fig. 3g). Raise a conservative flap of both the facial and lingual gingiva. A split flap is preferable, to prevent unnecessary trauma to the periodontal tissues, to provide maximal blood supply to the soft tissue graft. A microblade is helpful. Use microsurgical instruments to handle the soft tissue.

4. Use a gingival protector or similar elevator to reflect the flap and visualize the coronal root and bone crest (Figs. 3h-i). Further reduce the root to bone crest using a high-speed 1:1 surgical handpiece and bur with cooled, sterile irrigation (Fig. 3j). Several burs may be suitable. Preferably use a large round course diamond bur.

4.1 Option a) reduce the coronal root circumferentially to bone crest. Reduce the root further with the large round course diamond bur, creating a concaved shape to complement the future tooth pontic (Figs. 3j, 4a). Confirm the reduction clinically and radiographically (Fig. 4e).

4.2 Option b) reduce the coronal root to at least 2-3 mm below crest with an end-cutting bur. Reduce the center of the root to also create concaved shape to complement the future tooth pontic.

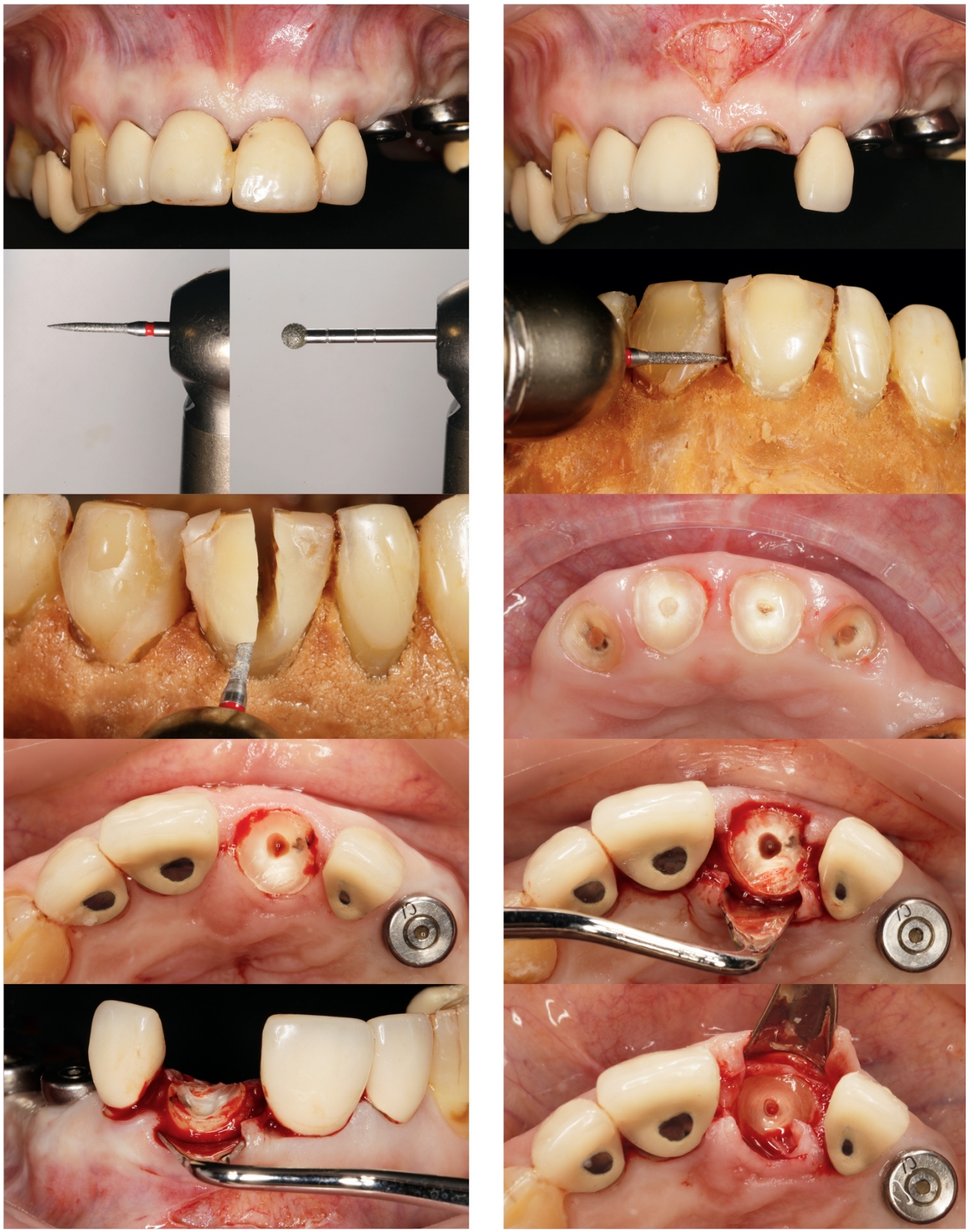


Figure 3: (a) Preoperative view. Tooth #9 fractured at cervical area. (b) Decoronate tooth initially with 2 mm coronal structure. (c) Rotary instruments. (Left) Narrow-tapered coarse diamond, to decoronate tooth. (Right) Large, round coarse diamond, to reduce apically, create concaved coronal root. (d) Cadaver model. Narrow-tapered, coarse-grit rotary instrument positioned at interproximal area. (e) Cadaver. To avoid damaging the papillae, first cut from mid-incisal toward apex, then laterally to remove crown. (f) Different example case. Resin-bonded fiber posts in position. Leave in position if immobile, free of pathology. (g) Sever gingival attachment circumferential to decoronated tooth. Sever the papillae. Both incisions made with size 15c blade or similar. (h) Gently reflect flap with gingival protector. (i) Gingival protector reflecting facial flap. Root periphery reduced to bone level. (j) Centre of root further reduced forming concave shape.

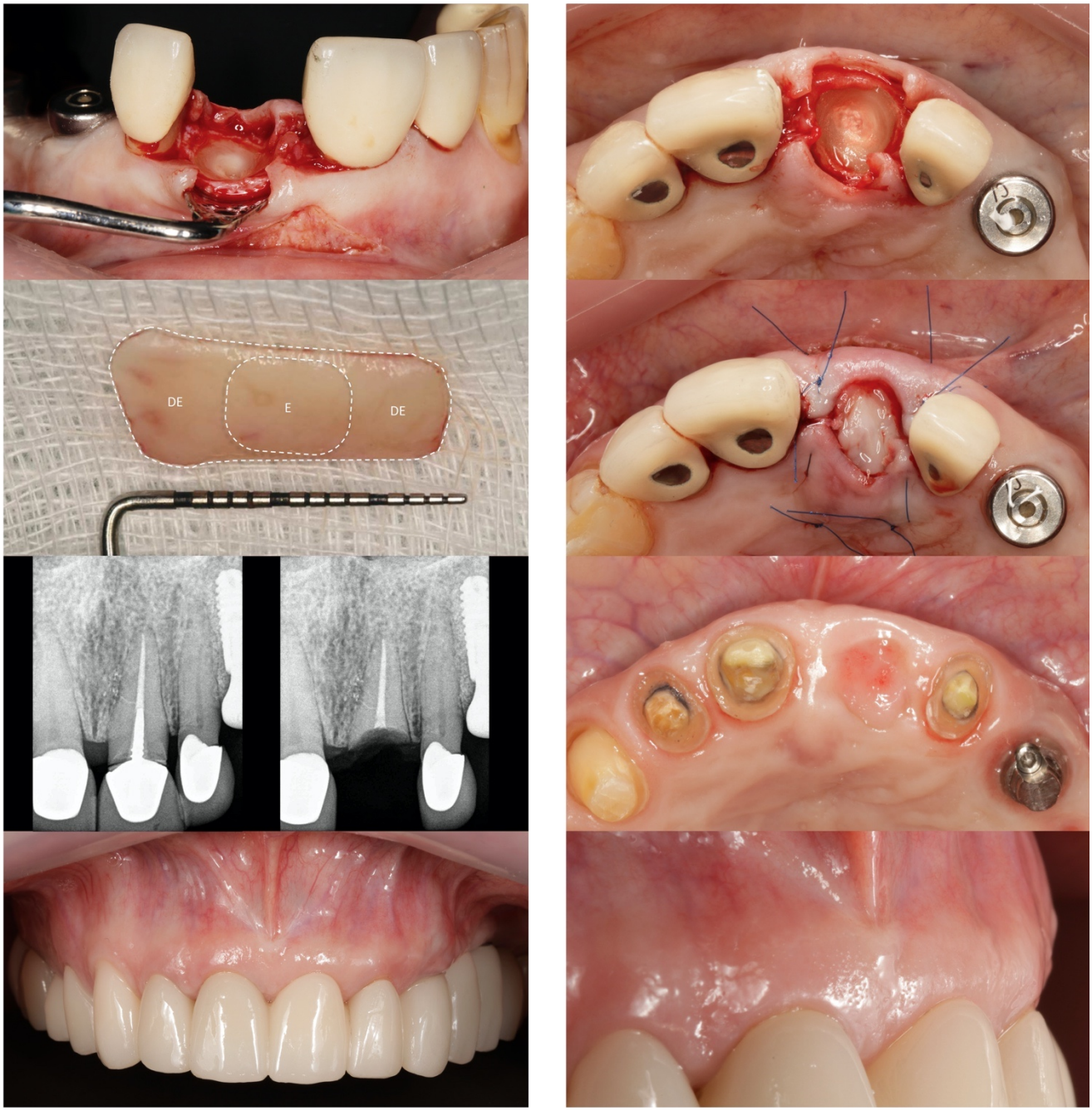


Figure 4: (a) Reduction to bone crest or below visually confirmed. (b) Bioactive endodontic cement used for coronal seal.(c) FGG from palate. Centre portion retains its epithelium - E. Remainder of graft is de-epithelialized - DE with a scalpel blade after harvesting. (d) Soft tissue graft secured in position. (e) Radiographs. Pre-op left, post-op right. (f) Occlusal view of healed site. Pontic pressure has developed soft tissue. (g) Complete cases, frontal view. (h) Completed case, oblique view.

5. If submerging a vital root, assess the root canal tissues once coronal reduction is complete. Use subjective endodontic diagnostic skills. If no bleeding, necrotic tissue, or hyperemic bleeding, endodontic treatment is required. This is the exception mentioned in step 1. Use of rubber dam and coronal clamp should be possible. Due to surgically exposed tissues, take explicit care with the endodontic rinse. Use liquid dam sealer and suction judiciously. Seal the root canal and take the radiographs to confirm treatment is adequately completed. The second exception is a non-bleeding root canal due to calcification. Use clinical judgement. Calcified canals might not require treatment. The author of this thesis recommends endodontic treatment in such cases.

6. Use clinical discretion whether to seal the coronal canal of the endodontic-treated root. The current author recommends coronal seal as essential. If choosing to seal, a bioactive endodontic cement may be first choice (eg. Biodentine, Septodont, USA). Remove 2 mm of coronal canal sealant, and place cement in this coronal space (Fig. 4b), which supposedly sets within 10-12 minutes. Mineral trioxide aggregate (MTA) is not the material of choice, as it takes 4 hours to set. In fact, both cements are very difficult to handle and have unpredictable setting times. Glass ionomer is also not recommended. Note that vital roots do not require coronal seal.

7. Submerge the fully prepared root under a soft tissue graft. Use either a CTG or a partially de-epithelialized FGG. Select any harvest technique from the palatal mucosa that would suffice. If harvesting a FGG, remove the epithelium from the periphery of the graft (Fig. 4c). Submerge the root beneath the graft such that connective tissue is positioned beneath the flaps, and an epithelium covered mucosa faces the oral cavity and tooth pontic (Fig. 4d). The graft is secured in position with sutures (preferably nylon 6/0 or 7/0 diameter).

8. If submerging 2 or more adjacent roots beneath a short-span prosthesis, repeat steps 1 through 7 for the additional submerged root sites. Use a soft tissue graft of sufficient size to ensure all roots are adequately submerged.

9. Restore ridge preservation site with a pontic tooth, its ovate surface applying moderate pressure the soft tissue graft. Ensure adequate space between root and pontic. Use clinical discretion to shape the pontic tooth's ovate fitting surface and interproximal spaces to develop the soft tissues. Start developing the soft tissue contours of the site immediately in this manner. Use a provisional restoration such as a bonded Maryland FPD denture, a tooth or implant-supported FPD denture, Essix retainer with a pontic tooth, or even a suitable removable partial denture (RPD). Make a final baseline radiograph of the submerged root (Fig. 4e).

10. Proceed to the definitive restoration after sufficient healing and maturation of the soft tissue (minimum 2-3 months) (Figs. 4f-h).

Discussion

Despite being reported on in 47 studies in both humans and animals between 1971 and 2015, a detailed step-by-step description of the RST has not widely been available. Provided here is the PET protocol for submerging roots at single or short-span edentulous sites. The literature reports that complications occur, specifically exposure of the roots (Table S5). These are due to poor technique. The roots must be adequately reduced. Decoronation and reduction to bone crest level at minimum is mandatory. Histological reports have confirmed coronal bridging (Fig. S13). This is referred to as coronal bridging, and would contribute to separating the submerged root from the oral cavity, ensuring mucosal integrity, and the sites to endure long-term free of disease. When the roots are further reduced to 2-3 mm below bone crest, histological and radiographic data have confirmed complete coronal bridging by bone (83, 84, 86).

After raising full-thickness mucoperiosteal flaps, crestal bone loss may occur, and roots initially reduced to bone crest might after healing be positioned above the crest, leading to possible exposure (66). Also, fully edentulous jaws and long-span edentulous sites restored by full removable dentures remain a unique scenario separate from single to short-span edentulous sites described in this technique report. Larger flaps with vertical and periosteal release incisions may allow for passive flap advancement, but result in a loss of vestibular depth (98). This is a particular problem at full removable dentures. At FPD, this is less of a problem, since support and retention is not influenced by the ridge and vestibule. Regardless, at almost all RST sites a soft tissue graft is required. Previous authors incorrectly managed submerged roots beneath FPD, expecting the soft tissue to fully granulate over the avascular coronal root (91). Incomplete healing and exposure of the root to the oral cavity may occur. Moreover, clinically the mucosa may appear mostly or fully healed, yet histological examination has confirmed fistulae, ingress of bacteria, and inflammation (86).

That said, there are few scenarios when a soft tissue graft might be omitted, namely:
1. In very rare cases when the submerged root(s) and ridge are reduced. Treatment without a soft tissue graft may be possible, because the flaps are not advanced and the vestibular depth is not reduced. The reduced ridge allows for adequate, even excess, attached keratinized gingiva from both the facial and the lingual to be passively adapted over the root(s).
2. When a flap is advanced at submerged roots beneath a FPD. This allows for healing by primary intention, but the vestibular depth is reduced. At a FPD (unlike the impact on a removable denture flange) this may be acceptable.

To summarize, key to success is correct root and flap management. Seal and cover the submerged roots with a soft tissue graft as described in this report, or a similar CTG of sufficient size and technique of one's choosing. Integrity of the overlying mucosa is key to long-term success with all PET.

V.1.5 The root submergence technique at long-span and fully edentulous jaws

At single sites to short-span edentulous areas, especially beneath FPD, the RST is highly successful. Removable dentures however present a challenge. The data reports that exposures more frequent than at removable dentures. Also, advancing flaps reduces vestibular depth, restricts the denture flange, the flange contributes to dehiscence of a healing wound, and the physical impact of the denture on the submerged roots also contributes to the complications (Table S5). An additional challenge is dental/skeletal malocclusion – patients with vertical maxillary excess. Compared to single-sites, submerging multiple roots when treating full arches and long-span edentulous areas beneath removable, non-implant-supported prosthetics is a significantly more extensive surgical and restorative procedure. Thus, specific approaches are required as outlined hereafter.

Technique

1. Assess and diagnose each tooth planned for submergence – its individual pulp status, and/or existing

endodontic treatment (Tables S10, S11). If endodontic treatment is required additional to submerging the root, this should always be completed prior to decoronation and surgery. Make every attempt to isolate with rubber dam and clamp, even if crown/coronal structure is lacking. Providing endodontic treatment during surgery is not ideal. A rubber dam may not adequately protect the surgical site from the endodontic rinse after decoronation and raising a flap. Bleeding also compromises moisture control. The exception is a tooth previously diagnosed vital, presenting with a diseased pulp after being decoronated – discussed in step 2.4.

2. Proceed to step 2.4 if the tooth crown is absent or mostly absent. If the tooth crown structure is present, decoronate the tooth by cutting the crown approximately 2 mm above gingival level. Section the crown from the tooth by cutting horizontally/mesio-distally with a high-speed dental handpiece with an irrigated rotary instrument. A narrow, tapered, diamond bur is ideal for this purpose. Section at first to a supragingival level. This protects the soft tissue, and also allows for coronal structure to later fix a rubber dam and clamp if needed. Cutting adjacent teeth during this step is not a risk, since all teeth are being submerged (and/or extracted).

2.1 Start cutting from the interproximal area if space for the rotary instrument is adequate. Cut the crown in a horizontal sawing motion toward to the opposite interproximal space. Moving only in a horizontal motion risks the rotary instrument becoming lodged in the crown. Thus, cut both horizontally and facio-lingually. Use abundant, cold irrigation during this step.

2.2 If there is no interproximal space to fit the rotary instrument cut first vertically from the mid-incisal/occlusal point, as described section V.1.4. Alternatively, cut vertically through the contact point of two crowns, and then continue horizontally to section the crown as per step 2.1.

2.3 Take care when decoronating heavily restored and previously endodontic-treated teeth. These are prone to fracture. Teeth with adequate post-and-core, crown, and previous endodontic treatment: Section the crown as described, and leave the post within in the root, especially if secure and long within the canal (Fig.3f). Remove the post if it is mobile and short.

2.4 Once all teeth have been decoronated to an initial supragingival level, make a final assessment of the pulp statuses. Use a large round diamond rotary instrument to further reduce the middle portion of the root more apically (a concave shape) to access possible healthy pulp tissue deeper in the canal, and aid this diagnostic step. This would be evidenced by bleeding. A non-bleeding pulp is a risk. A necrosed pulp requires endodontic treatment. Conversely, a calcified canal may not require treatment. The clinician is to exercise their own discretion. At this stage, any additional endodontic treatment must be carried out with great care to isolate the tooth.

2.4.1 At tooth root sites requiring endodontic treatment or having periapical pathosis, one may select an alternative PET. Consider preparing a pontic shield instead (Fig. 10d), especially if the clinician is not inclined

to provide endodontic treatment. Thus, suitable roots may be submerged in full, and alternate roots with endodontic/apical pathology may be prepared into pontic shields (PS) and the remaining socket(s) grafted.

2.5 Vital roots do not require coronal seal. If endodontic treated roots are submerged, as stated previously, the current author recommends sealing of the coronal canal.

3. Start raising the flaps only after all tooth root pulps and/or endodontic treatment have been determined adequate to submerge. Select among the two options for flap design. Option 1 - make intrasulcular incisions circumferential around all coronal roots. Sever the papillae interproximal, and raise the flap with the papillae intact. Option 2 – make a horizontal incision at the base of the papillae, such that a straight-edge flap is later approximated for primary intention healing. The latter is not ideal if there is a lack of attached keratinized tissue.

3.1 Use one's discretion in either flap option 1 or 2 above, and whether to raise a full thickness or partial thickness flap. The latter is arguably more difficult. Conversely, adding a CTG/FGG to ensure closure of the soft tissue may benefit from a partial thickness flap (Fig. 4d). Regardless, use the correct micro-instrumentation, and always handle the soft tissue with care. In the majority of ridges, reflect both the lingual and facial flaps approximately 5-10 mm each only. Visualize the coronal root and alveolar bone crest. Ensure at least 5 mm of flap to cover the soft tissue graft for adequate nourishment.

3.1.1 Rare exceptions: for ridges with abundant vertical height and vestibular depth, there are two further options. Option A – raise a flap deep into the vestibular sulcus, make releasing incisions (whether vertical or periosteal or both), and advance these to ensure closure for primary intention healing. This will reduce the sulcus depth, but in an abundantly deep sulcus, might not be an issue. Option B – alternatively raise a conservative flap, and reduce the alveolar ridge (with the submerged coronal roots) such that the flaps adequately approximate without release and advancement.

3.1.2 In rare cases of ridge height reduction, use a large sterile carbide bur coupled to a surgical handpiece with abundant cold irrigation. Make initial depth cuts and reduce the adjacent ridge to this level.

3.1.3 Do not raise the flaps deep into the vestibular sulcus and advance these in the majority of cases. Most patients will not have excessively deep sulci, and the loss of vestibular depth may limit the extent of the denture flanges. This also negatively impacts passivity of the flaps, may contribute to dehiscence of the mucosal wound, and root exposure.

3.1.4 If, in exceptional cases, a deep flap is raised and advanced, periosteal release incisions (or rarely, vertical release incisions) must be made to ensure tension-free flap closure.

3.1.5 After selecting a flap management option, there are two further options with regards to coronal reduction

of the tooth roots. Option 1 – reduce the tooth roots to bone crest. Option 2 – alternatively reduce the coronal root circumferentially 2-3 mm below crest. For multiple adjacent submerged roots the latter is recommended. Literature also reports bone growth over submerged roots when reduced below bone crest (83, 87, 103). Use an end-cutting bur to cut the periphery of the root (Fig. 6b). Take care not to cut into the alveolar crest.

3.1.6 After fully completing decoronation of all roots and prior to flap closure, inspect the alveolar bone and ridge for any sharp prominences that may further need reduction.

4. Ensure full soft tissue closure of the submerged roots. As stated above, in a majority of cases the ridge should not be reduced, neither should the flaps be advanced. Therefore, graft the coronal aspects of the submerged roots with a CTG/FGG. Select any harvest technique from the palatal mucosa that would suffice. If harvesting a FGG, remove the epithelium from the periphery of the graft. Ensure the soft tissue graft is inserted at least 5 mm beneath the flaps for nourishment.

5. Secure the graft and flaps in position with sutures. Suture the papillae back together if these have not been excised from the flaps.

6. Make a decision whether to insert the full denture immediately, or not. The current author advocates not inserting dentures. Instead, first allow for two full weeks of undisturbed graft and soft tissue healing to better ensure submergence of the roots. Use discretion to temporarily support the denture free from impacting the healing tissues with interim mini implants. This however increases cost considerably. If mucosa-supporting dentures must be inserted, use a soft liner/tissue conditioner.

7. Provide clear postoperative home care instructions in print/writing. These address the main postoperative risk of wound dehiscence and exposure of the roots. Also give adequate post-operative medication. Do not routinely administer systemic antibiotics. Ensure the patient is administered adequate anti-inflammatory, analgesic drugs for the initial 1-2 weeks of healing. Add an anti-septic oral rinse, together with explicit instructions on use. Prescribe a soft diet and adequate fluids for the initial 2 weeks. If dentures must be inserted immediately, ensure these are not removed for the first 48 hours. Dentures are only removed at very short intervals for use of the anti-septic rinse.

8. Follow conventional full denture fabrication steps after the initial 2 weeks if uneventful healing. Manage early root exposures if they occur, by raising a very conservative flap, and additionally reducing the coronal root. Be equally conservative with the flap closure and sutures. Manage late exposures occurring after soft tissue healing in a similar manner. Take radiographs to confirm the root's endodontic/periapical health. Add a second conservative soft tissue graft to better ensure mucosal closure and full root submergence.

V.2 The socket-shield technique

V.2.1 Historic evidence and origins of the technique

Today, patients the world over have restorations supported by dental implants. If a tooth requires an extraction an implant may be placed immediately into its socket. Authors have however dissuaded clinicians against this approach, to rather opt for the "extraction-and-augment" convention (49). Survey results in section V.1.3 confirm this. The risks emphasized of IIP relate to unpredictable healing of the extraction socket, subsequent resorption, followed by biological and esthetic complication at the implant and restoration. Five decades ago dentists theorized that submerging roots would preserve the alveolar ridge, aiding the prosthetic treatment of their patients (85). A logical progression was the submergence of roots adjacent to dental implants, their attachment apparatus supporting the ridge at these implants (14). It is possible that the next step may have been reports of placing dental implants in contact with ankylosed roots or even directly through root impactions (122, 123). These successes may have progressed to the first ever report of a tooth root intentionally sectioned such that its facial root portion remains within the extraction socket, to preserve the ridge tissues facial to an immediate implant inserted lingual to it (15).

V.2.2 Counter-argument and evidence: Systematic review of the SST

Authors have made arguments against the SST. Risk, complication, and poor evidence appear the main points of dispute. Nevins et al in 2018 reported on two cases of "late dental implant failures associated with retained root fragments" (124). In both cases the implants were removed for analyses. The report concluded "unintentionally retained root fragments in proximity to dental implants may also contribute to late implant failures". Careful examination of the radiographic images indicate that wide implants were used at the site (Fig. S14). One may speculate that biological parameters are violated if too wide an implant is placed at a site with insufficient circumferential bone. The radiographs also show the graft was failing, with significant bone loss on the distal of the implant in case 1, separate from the root fragment on the mesial side of the implant. The retreated site clearly shows narrower implants of more appropriate size, with platform switch. Additionally, a counter argument could be that the SST is in no way an unintentionally retained root fragment. It is a deliberate and careful preparation of the root adjacent to an implant. There are explicit criteria for this preparation, including the removal of pathologic tissue (55). The conclusions of the report thus do not correlate with the SST, and cannot be directly applied to it. The same author had three years prior reported several more such cases, and the same debate applies (125).

In 2017 authors Gharpure and Bhatavadekar published a literature review to conclude that "overall evidence seems limited", "evidence indicates rapid bone loss" (126). The author of this thesis contested the review as fraught with errors (127). A systematic review was allegedly carried out "in line with the recommendations of the PRISMA statement". However of the 23 studies (though 2 were listed twice) tabulated by the authors to review "complications and adverse effects", several were not the SS (128-130) 3 were misrepresented as adverse

effects (15, 131, 132) and 11 of the remaining 16 reported no complications. Of the 5 studies tabulated for complications, 4 reported bone loss within the expected parameters for IIP. 1 study reported loss of SS in 1/16 patients, and another study reported a probing depth of 8 mm at 1/23 SS (127).

The article clearly lacked scientific rigor. The authors stated "The objective of the systematic review was to assess the literature available on the SST and weigh its biological plausibility and long-term clinical prognosis". Viz the first step to a systematic review is to frame the research question, yet a clear and unambiguous question was absent. Rather, an "objective" was proposed. The authors thereafter duly identified eligible literature resources, namely "a PubMed-Medline, Embase, Web of Knowledge, Google Scholar and Cochrane Central [for clinical/ animal studies] up to April 2017". The eligibility criteria for reviewed articles were the greatest error. “Studies were included if… implants are placed in close proximity to or in contact with root fragments which are intentionally retained to preserve or promote buccal/proximal/crestal bone”. Exclusion criteria were, studies (1) in which root-fragments were not left back intentionally to preserve or promote buccal/proximal/crestal bone and (2) in which implants were unknowingly placed in proximity or in contact with retained roots. Throughout the article was evidence of this eligibility not being adhered to.

1. Section: " Study characteristics and outcomes", Table 1 in article
- The review referred to Parlar et al, 2005, as “the first to place 18 implants in the center of prepared hollow chambers of decoronated roots having slits at the periphery in nine mongrel dogs" (128).
- Parlar and coworkers never intended to evaluate bone preservation as a function of retaining hollowed out tooth roots and placing the implants within the center of a tooth root chamber.
- The original article read: "The purpose of this study was to explore the formation of periodontal tissues around titanium implants using a novel and unique experimental model." Also, "This study aimed to investigate the possibility of formation of cementum and periodontal ligament on titanium surfaces in a novel experimental model in which the priority of repopulation on titanium surface is given to periodontal ligament cells".
- There was no evidence that Parlar and coworkers' aim was to evaluate bone preservation by the SST.
- Ergo, the review of their work included literature not meeting the inclusion criteria.
- Moreover, the data had been combined with other animal histological studies in Table 2, and misleadingly mixed these to draw conclusions on “Total complications and adverse effects”.

2. Section: "Study characteristics and outcomes", Table 1
- A study by Troiano et al, 2014, was cited that also did not meet the review’s selection criteria (130).
- Troiano et al did not evaluate the SST. As with the experimental failure by Parlar et al, Troiano et al also placed implants inside tooth roots. That was not the SST.

3. Section: "Study characteristics and outcomes", Table 1
- Another study was cited by Guirado et al, 2016, also not meeting the selection criteria (129).
- Guirado et al placed implants wholly inside the center of teeth in 6 dogs. Their study also did not evaluate the

SST. As with previous studies, dating as far back as Buser et al, 1990, placing dental implants inside tooth roots consistently fails to achieve osseointegration (133).

4. Overstating the extent of bone loss resulting from the SS was also misleading. Bone loss was attributed to studies of entirely different procedures as stated above. Also, it is now well established in the literature to anticipate approximately 2 mm of crestal bone loss following IIP. In fact, according to Chappuis et al, 7.5 mm vertical bone loss is expected at maxillary central incisors in thin-wall phenotypes (22).
Throughout the review , the results for bone resorption were reported as: “Mean crestal bone loss 0.8 mm", “Mean buccal bone loss 0.72mm", “Mean crestal bone loss 0.18 ±0.09 mm mesial 0.21 ±0.09 mm palatal”, “Mean buccal bone loss 0.88 mm Range - 1.67 mm to 0.15 mm”.
- Additionally, an article by Siormpas et al was cited to as having “adverse effects”. Siormpas et al reported 1/46 patients to have 1.5 mm root resorption, with no other adverse effects reported (134).
- Lagas et al reported loss of a SS in 1/16 patients, and this implant was still restored with positive outcomes reported (135).
- A further 11 articles were nominated in Table 1 to conversely have "no adverse effects".
- The review tabulated results from incongruent articles, reporting on techniques that were not the SS, and inaccurately presented interpretation of these to overstate adverse treatment outcomes, when contrary to established literature all the results fared better in terms of bone loss than conventional IIP.

5. The review authors stated: “loss of the SS either by resorption or due to extraction following infection, may lead to loss of the bone it preserves and may predispose the implant surface to exposure”. Yet there is no evidence of this in the literature. Also, replacement resorption of a SS by bone, should find bone on the facial of an implant, which is a positive outcome.

The review made numerous additional errors and strayed far from the main aim of assessing "long-term prognosis and biological viability" of the technique. Biological viability was almost entirely omitted from the review. The authors stated “only 5 studies could be included for the modified ARRIVE quality analysis”, which was equally problematic. The ARRIVE guidelines apply to animal research exclusively (136). The acronym literally stands for Animal Research: Reporting of In Vivo Experiments. The review could only apply the guidelines to the 5 animal research studies cited. It was thus misleading that “all the clinical studies”, the majority of which were human case reports, failed to meet guidelines exclusive to animal research.

To conclude this section first section on the SS that addresses a pros and cons analysis, caution when reading the published literature is highlighted. Even the research produced by this thesis requires a discerned scrutiny to balance results against limitations. Though pooled data are published, it is imperative that these are an accurate representation of specifically selected results.

V.2.3 Retrospective data: 128 socket shield cases with up to 4 years follow-up

In 2017 the author of this thesis published on the largest cohort of SS cases at mid-term follow-up (51). Data was collected from a private practice database. Inclusion criteria restricted records to all patients who previously had SST, a minimum of mid-term follow-up (≥ 12 months), follow-up verified at minimum by clinical examination with periapical view radiograph and photograph, follow-up start date defined as day of restoration (provisional or definitive), and all treatment failures and complications to be reported (at placement, during osseointegration, during provisionalization, or post definitive restoration). Patient records were excluded if the implant was not loaded with a restoration (provisional or definitive) for at least 12 months, or if the patients were unable to return for follow-up evaluation. Patients identified from the treatment database were invited to return for a recall evaluation and selection criteria as above were assessed. All implants evaluated in this study were internal, morse-taper-like, or conical connection implants only. Diagnostic records at the follow-up visits were evaluated. The primary outcome measure was implant survival. Secondary outcome measures included implant failure, signs of peri-implant mucositis or peri-implantitis, and/or other complications (SS exposure, infection). Data were compiled into an electronic record for analyses.

Of the totaled results returned, 128 cases met the selection criteria. 70 immediate implants with SS were placed in female patients and 58 in males. Patient age ranged 24-71 (mean 39 years). Maxillary incisors were treated most often (64%), premolars second most often (22%), and canines least often (14%). Maxillary sites were treated far more often the mandible (89.9% versus 10.1%). A total of 25 complications occurred (19.5% total complications rate). 20 were minor, whilst only 5 of these implants failed during the initial osseointegration/healing period. 16 SS encountered exposure. 3 sites developed an infection. 1 SS migrated/over-erupted (Table 3).

Tooth site	Exposure (internal)	Exposure (external)	Infection	Implant failure	Migration	Timing of complication	Management
21				1		At integration check, 3 months	SS intact, implant replaced, osseointegrated,
11	1					At integration check, 3 months	SS reduced, soft tissue healed, restored
21	1					At integration check, 3 months	No treatment, no additional complications
33		1				1-year postop	Reduced, CTG, soft tissue healed, restored
21			1			2 months postop, prior to integration check	SS removed, implant cleaned, GBR, restored
13				1		At integration check, 3 months	Implant replaced, restored, shield intact
12, 11		2				1-month postop, prior to 3 months integration	SS reduced, soft tissue healed, midfacial recession
12	1					At integration check, 3 months	SS reduced, restored
21		1				2 months, at exposure of adjacent implant	SS reduced, CTG, soft tissue healed, restored
12			1	1		1-month postop	SS & implant removed, healed, implant + GBR restored
11			1	1		1-month postop	SS & implant removed, GBR, FPD
21	1					9 months, at delivery of definitive crown	No treatment, no additional complications
11	1					At integration check,3 months	SS reduced, restored
11	1					At integration check, 3 months	No treatment, no additional complications
21	1					9 months later at final check before final crown	No treatment, no additional complications
21	1					At integration check, 3 months	No treatment, no additional complications
23	1					At integration check, 3 months	No treatment, no additional complications
22				1		4 months, at time of exposure of adjacent implant	Implant removed, RPD
11, 21	2				1	Exposure at 9 months. Migration of shields at 3 yrs	No treatment, no additional complications
34	1					At integration check, 3 months	SS reduced twice, soft tissue healed, restored
Totals	12	4	3	5	1	Mean 4 months	25 sites in total, 17 managed and 8 monitored
SS = socket shield							

Table 3: All complications and management during this study. (Proprietary image of Wiley-Blackwell publishing, Clinical Implant Dentistry and Related Research)

Complications and management

Implant failure

It is not possible to determine with certainty whether the 5 implants that failed to osseointegrate were a result of the additional SS procedure. All 5 implants were removed and the sites were managed. 3/5 SS were still intact and without pathology, infection etc. The sites were cleaned and the failed implant replaced in 2/5 cases. Both retreatment implants osseointegrated and were restored. In 1/5 cases the implant was removed and the site converted to a PS. In the 2 other failures, patients opted for a FPD and RPD respectively. Both SS and implant were removed and these 2 cases re-treated.

Infection

3 SS were mobile, developed an infection. In 1 case the SS was mobile and removed. The site was exposed and cleaned, the exposed surface of the implant decontaminated, grafted with a GBR procedure, and later restored. In the other 2 cases the SS and implant were both removed. In 1 among those 2 cases, another implant was later placed, the implant osseointegrated and was restored. In the other case the site was grafted and later restored as a pontic site beneath a FPD.

Exposure

Exposure was the most common complication encountered. This is defined as perforation of the coronal SS through the overlying mucosa, and may be subdivided into internal exposure (toward the restoration) or external (toward the oral cavity). The incidence of internal exposures (12/128) exceeded external (4/128), 9.4 % of all cases vs. 3.1 %. All internal exposures were managed by either no treatment and observation, or by reduction of the exposed root portion with a diamond bur coupled to a high-speed handpiece. 4 external exposures occurred, all of which were managed by reducing the coronal aspect for soft tissue closure. 2/4 external exposures were augmented with a CTG to assist soft tissue healing. In a case of external exposure in the same patient of both sites 11 and 21 (#8 #9), the SS were reduced for soft tissue heal over, with a final healing outcome of 2 mm midfacial recession.

Migration

1/128 SS migrated. In this patient, SS at sites 11 and 21 (#8 #9) demonstrated internal exposure when the provisional restorations were removed at impression taking. 1 socket shield had migrated (confirmed on CBCT scan). The prosthodontist restored both implants without reduction of the SS and both have been monitored without additional complication.

Discussion

123/128 implants osseointegrated and survived 1-4 years following restoration (survival rate 96.1 %). 5 implants failed to osseointegrate and were removed. The remaining 17 complications were all managed or monitored without management and definitively restored, all surviving at mid-term follow-up. Subjective evaluation of the definitive restorations at follow-up identified 2 mm tissue recession at adjacent SS after reduction in 1 patient.

No other situations of recession sufficient to expose the implant-abutment interface or implant to the oral cavity were noted. Blue-gray hue as a sign of implant translucency through the gingival tissue was not noted in any cases. Signs of peri-implantitis, clinically or radiographically, was not noted in any of the cases followed-up. The main complication noted was exposure of the SS. As such the technique has required some additional, minor modification, discussed in section V.2.4.2.

Conclusions

This study reported on the largest cohort of SS at mid-term follow-up. The aim was to report first on the survival rate of immediate implants adjacent to the SS. Data confirms implant survival to be comparable to conventional IIP, as well as early and delayed treatment rates.

V.2.4 Human histologic data: Bone formation between root portion and dental implant

Previous animal histology have provided valuable evidence of the healed SS and implant (15, 139). Such data in humans is rare (59). It thus would be unclear what tissues consistently heal between the SS and implant. What are the clinical implications if these tissues differ from conventional implant treatment? To answer these, human histological evidence was presented in a 45-year-old female patient following the removal of her implant in site 24 (#12). The patient had an immediate implant that was apparently successfully restored. During routine follow-up two years later the treating clinician noted a 6 mm probing depth at the mesiobuccal area, and what appeared to be the root remnant of an incompletely extracted tooth 24 (#12). A diagnosis of peri-implantitis was made, and together with the erroneous, incomplete extraction, patient and dentist both opted for removal and retreatment of the site. The implant together with the surrounding tissue was removed en-block for histological examination. The site was grafted, healed, a second implant placed, and later also successfully restored.

Histological analysis

The implant with adherent tissue was fixed in 10 % neutral buffered formalin, dehydrated, infiltrated, then slow embedded in a glycol methacrylate-based polymer resin block, and cut by microtome into undecalcified sections. The sections were then polished to within 10 microns and stained with Stevenel's blue and van Gieson picro fuchsin. Viewed at low power (25 X) under light microscope, an adherent root section was observed extending the vertical extent of the implant approximately 3 mm coronally beyond the first thread and implant collar (Fig. 8a). The fragment was verified as a tooth root, displaying dentinal tubules that spanned the dentin layer and interfaced with an outer cementum layer. At medium power magnification (40 X), the dentinal tubules were distinct (Fig. 8b). A lateral root canal was also observed at about the apical third of the implant. Tissue was present within the implant apical chamber and between the implant threads. The tissue contained in the apical chamber and that which filled the implant’s interthread spaces was confirmed as bone, displaying a marbled appearance – the resting and creeping reversal lines typical of alveolar bone’s histological presentation. This tissue was intimately apposed to the both implant surface and the root section. The bone that occupied the interthread spaces, when viewed by polarized microscopy, exhibited mineralization with concentric lamellae,

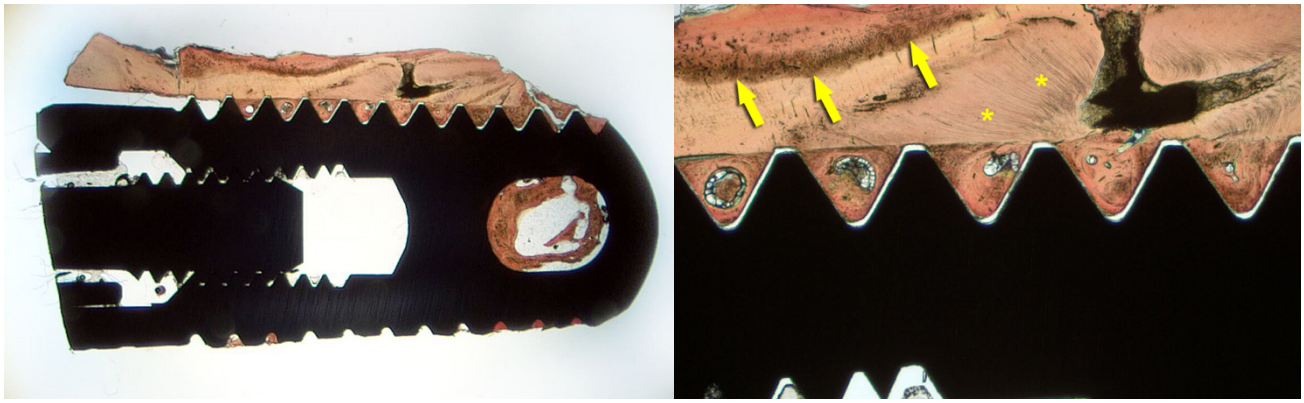


Figure 5: (a) Longitudinal section of implant with attached root section removed from patient. (b) Higher magnification, dentinal tubules (asterisks) and the cementum layer (arrows). Note that bone fills the inter-thread spaces between implant and root. (Proprietary images of Quintessence Publishing, The International Journal of Oral and Maxillofacial Implants)

evident of mature, remodeled bone. The space between implant surface and bone was a separation artefact that likely resulted from the microtome preparation of the sample.

Discussion

Several studies have attempted to experiment with growing periodontium onto dental implants instead of the "functional ankylosis" that is osseointegration (128, 133). All have failed to produce clinically beneficial results. As such, the clinician contemplating the SST may have concerns what tissues grow between it and the implant. The distinction though is to be made regarding the root section configuration, and the origin of the mesenchymal cells that have osteoblastic differentiation potential. In the study by Buser et al, the authors demonstrated that a cementum layer formed on the implant surfaces and that a PDL consistently was present, inserting fibers from implant cementum into adjacent bone (133). Fifteen years later Parlar and coworkers similarly investigated the potential for periodontal tissues to form around dental implants (128). In an animal study teeth were hollowed and implants were inserted wholly inside the teeth. Slits in the teeth were prepared to allow passage to the periodontal ligament. Their results also failed to demonstrate successful osseointegration. These root configurations were however vastly different from the SS. As stated in the technique reports of this section, the SS is a precise, deliberate preparation of the facial root portion with its physiologic attachment to BB maintained. The SS in its orientation does not obstruct the passage of peri-vascular pluripotent cells and trabecular bone-lining mesenchymal cells to the implant surface. It may be inferred that the SS does not interfere with adequate osseointegration, and merely serves to support the tissues facial to the implant. Adequate osseointegration has been proven (51). In this human histology, a vertical root segment that spanned implant apex to collar was observed to interface with bone and the bone with the implant. Thus, this rare data confirms that it is possible for bone to grow between a SS and a dental implant.

V.2.5 Animal histologic data: Healing outcomes at different socket shield preparations

There are infinite unanswered questions regarding the SST. Retrospective data has identified that supracrestal

preparation frequently results in exposure. What then about the other preparation aspects? How long should the SS be? How thick? To address these an animal histological trial was carried out (58). The study was approved and registered with the ethics committee of the Rof Codina Veterinarian University Hospital, Lugo, Spain (01/ 16/ LU-001). 7 adult beagle dogs of same age and weight (mean 33 months, 14.1 kg) were selected for the study and quarantined by a research veterinarian team. The team ensured a controlled diet and living environment, according to prescribed European Animal Research Association (EARA) guidelines (140). This study has been reported in accordance with the ARRIVE (Animal Research: Reporting of In Vivo Experiments) guidelines (136). The pilot study formed part of a larger experimentation that compared immediate to delayed implant placement in the lower jaw sites and the effects of micro-threads, and so forth. For the SS portion of the study, the upper third premolar tooth on the right side only of the 7 beagle dogs were partially extracted and prepared as SS and implants immediately inserted. For experimentation, variations were prepared in the SS: width, length, supracrestal height, beveled and non-beveled. No flaps were raised. Only the buccal gingiva was carefully reflected with a gingival protector. All implants and components were of the same length and diameter (IPX, Galimplant). The buccal gaps were not grafted due to limited space. Transgingival healing abutments were fixed to 6 implants and a cover screw placed at 1. The animals were given an oral plaque control regimen, cleaning the teeth with gauze soaked in 0.12% chlorhexidine rinse 3 times weekly during weeks 1 and 2, then 3 times weekly by toothbrush and 0.12% chlorhexidine gel during weeks 3 to 4. At 90 days of healing the animals were sedated with IM metodamine at 20 mg/kg and euthanized by IV sodium pentobarbital at 40-60 mg/kg. Block sections of the jaws were harvested from the experimental sites and prepared as undecalcified sections for light microscopy.

Results

In the greater study investigating other parameters related to dental implant therapy, 70 implants were placed in the mandible. Of the maxillary implants, 7 were placed in the 3rd premolar site in conjunction with an attempted SST. 4 of the 7 implant sites incurred surgical injury to the infraorbital foramen and neurovascular bundle, confounding the observations of the implants and tissue healing. This pilot study produced 3 histological sections viable for observations. Detailed views of the sections are presented in supporting information, Fig. S15.

Section 1. SS preparation: Adequate vertical length, extending ≥1 mm above the bone crest (supracrestal).

Here the histological section demonstrated osseointegration of a dental implant with a transgingival healing abutment fixed to it (Fig. 9a). On the buccal aspect a root portion is seen – the SS. The SS was prepared with adequate vertical length, approximately one third to half the implant's length. It appeared to have its canal contents and apex correctly removed. However, the coronal portion was prepared ≥1 mm above the bone crest. The most coronal edge appeared sharp, a feature that may contribute to perforation of the overlying soft tissue. Surprisingly, the gingiva healed over the edge regardless (red arrow). The coronal portion of the SS had a shallow internal beveled chamfer prepared, albeit not ideal in design. Soft tissue filled the coronal prosthetic space (asterisk). The implant was in contact with the SS in areas and bone filled the majority of spaces between

these. There appeared to be bone fill of the healing extraction socket, with adequate bone to implant contact on the coronal and buccal aspects. The SS buccal PDL space appeared obliterated in areas with ankylosis. The buccal bone crest was also higher than the lingual. The apico-palatal portion of the socket farthest from the SS was lacking bone fill as yet (orange arrow). Though, this may have been the normal medullary presentation in this animal. The apical socket appeared intact with an isthmus of bone overlying the infraorbital canal's neurovascular tissue (green arrow). This was evident at higher magnification. Implant threads were in near contact with the SS at two foci and new bone filled most of the space between these (woven coronally, lamellar apically). The SS buccal PDL space was obliterated by ankylosis. At the most coronal portion, the soft tissue appeared edematous with inflammatory cell infiltrate. The internal beveled chamfer provided additional space for soft tissue infill. Resorption lacunae were noted in the root with new lamellar bone compensating for the tooth tissue loss, viz replacement resorption. Sharpey's fibers were evident at the bone crest. Immediately below, the PDL space was obliterated.

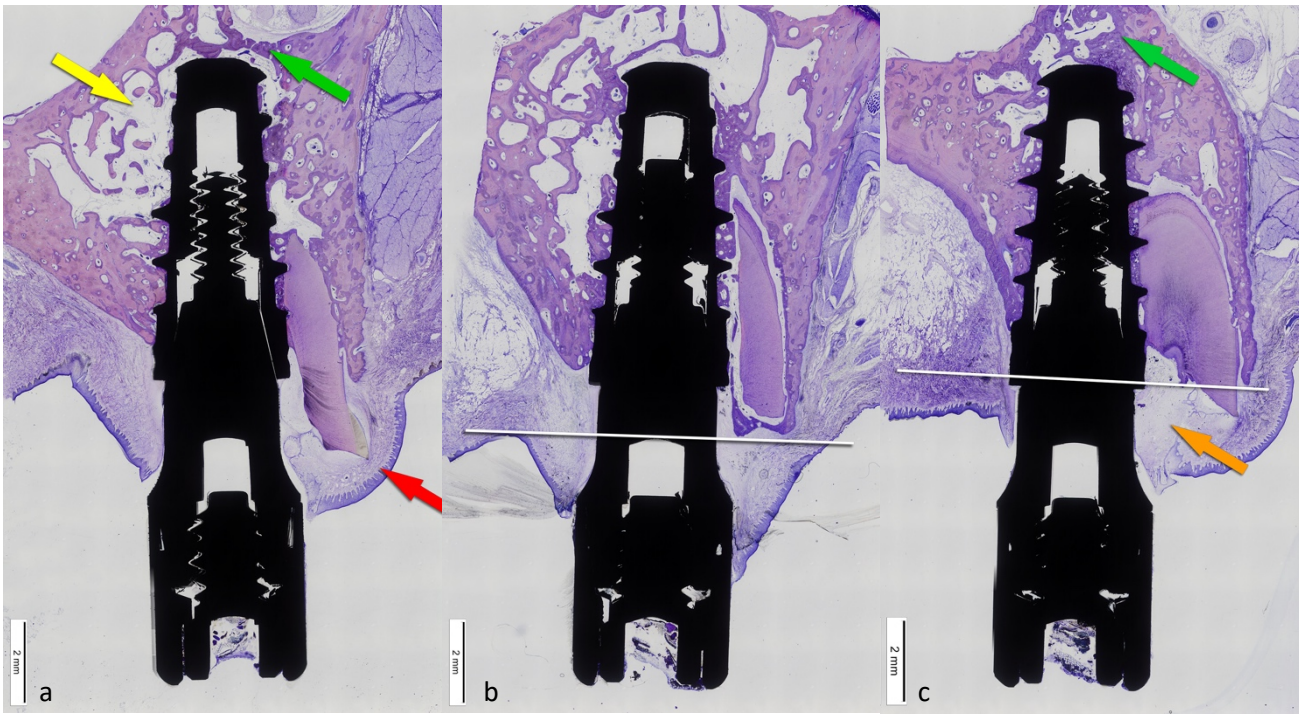


Figure 6: Full sections of the three implants with healed socket shields analyzed in this study. Annotations in section V.2.6

Section 2. Socket-shield preparation: Adequate vertical length, thinner buccolingual, reduced to bone crest, with an internal beveled chamfer.

This section showed an osseointegrated implant with adequate bone to implant contact (Fig. 9b). A transgingival abutment was fixed to the implant, both buccal bone crest and soft tissue positioned more coronal than the lingual. The SS was prepared about half to two thirds the implant's length, but thinner than section 3. The canal contents and apex were correctly removed. A beveled chamfer was prepared at its corono-lingual aspect, albeit modest and less defined than in other sections. This area provided prosthetic space with a bulk of buccal soft tissue infill. Bone healed over the coronal aspect of the SS, continuous with the buccal bone plate. This

histological presentation was absent from the other sections. Only in a single area was there bone noted to interface directly with the SS dentin facing the implant. There were signs of root resorption throughout the SS. There were miniscule amounts of new cementum in some areas. The control tooth site did not present this new cementum.

Section 3. Socket-shield preparation: Adequate vertical length, prepared thicker, almost at bone crest, with an internal beveled chamfer.

This section showed an osseointegrated implant with high bone to implant contact (Fig. 9c). The internal beveled chamfer provided additional prosthetic space (orange arrow). The implant apex did not perforate the infraorbital neurovascular tissues (green arrow). The implant threads were in contact with the SS and no adverse reaction was noted. Nearly the entire space between SS and implant surface (albeit limited) was filled with bone. Bone extended between implant surface and SS, up to its most linguo-coronal aspect. The most bucco-coronal aspect of the bone crest was supported by its PDL attachment to the SS. The SS PDL space appeared well-defined. There was a single, miniscule area of replacement resorption. A line from the buccal bone crest indicates it was supported more coronal than the lingual crest. There was a remnant of the root canal tissue, the implication though unclear. Despite the supracrestal extension of the SS, the gingiva had grown over and healed against the implant abutment. Nonetheless the buccal soft tissue appeared strained and thinner over the SS than the lingual.

Discussion

This pilot study provided some insight into the histological presentation of the peri-implant tissues when variations of the SS were prepared. The samples and resultant images were precious and few. The study was limited by its small sample size and absence of a control group, ie. conventional IIP. Preservation of the buccal bone crest was demonstrated, despite being friable and expected to resorb. This finding differs from animal histological data demonstrating greater resorption of the buccal crest when the tooth is removed (17).

In studies by other authors, the healing outcomes in differing crestal preparations of the SS were confounded by raising flaps (141). In keeping with minimally invasive dentistry, the SST unless combined with multiple other PET does not require raising a flap. The current study's authors concede that while the histology presented answers some questions, the findings elicit many more. The unfamiliar surgical anatomy in the beagle dogs' upper jaws presented a significant challenge, with limited bone volume, and with nearby structures of risk. In several of the specimens the dental implant procedure erroneously perforated the infraorbital canal or its foramen. The subsequent trauma and inflammation obscured notable observations of the resultant histology further limiting the sample size.

What was clear from the histology were two SS preparation features. When the coronal portion was prepared ≥1 mm above crestal bone, the overlying tissue appeared thin and constrained (sections 1, 3). It was unclear whether this supracrestal preparation as advocated in Hürzeler and Siormpas' techniques may have later lead to exposure in this study, but clinical data has demonstrated internal and external exposures through soft tissue when the SS is supracrestal (51). Moreover, in section 2 the SS was prepared at bone crest level and bone had

grown over the SS such that buccal bone and the bone between implant and SS were contiguous. Whether this histological finding is reproducible in human patients remains to be shown.

Previous studies have reported on the benefit of soft thickness at implants (142). The ideal situation is possibly achieved when the SS is carefully reduced to bone level, with its corono-lingual prepared to an internal beveled chamfer (53). The chamfer is not very pronounced in section 2, but should be about 2 mm apical from the coronal limit of the SS. This allows for an "S-shape" prosthetic emergence profile that does not restrict the soft tissue nor apply orthodontic force to the SS. The second distinct preparation feature is the performance of a robust and thicker SS (sections 1, 3). It is possible that an overly thin SS (prepared beyond ± ½ the thickness from root canal to facial root surface, or less than 1 mm thick) may result in flexure and fracture, especially if the implant threads contact it. Lastly, some degree of surface resorption of the SS has been observed (albeit not reported) in previous histology presented (15). Surface resorption was also noted in this study (Fig. S15). The overall impact is not yet known. In the absence of infection, resorption of the SS with bone substitution is a positive outcome. These and many other aspects discussed here remain to be clarified.

V.3 Technique reports

V.3.1 The partial extraction therapy protocol for the socket-shield technique

On its 10-year anniversary, the current author published the PET protocol for the SST (55). Much had developed and evolved over the since it was first introduced. For a treatment to be widely accepted, its procedures and the outcomes need to be reproducible and predictable for the majority who provide it. A standardized protocol provides a better framework for clinicians to report data of a technique with procedural consistency. Surprisingly, the original 2010 report did not provide a detailed protocol (15). In fact, it appeared to have been reported as a "cool" experiment, but one that should not be repeated in daily practice. A decade on, the result of much experience and research of the SS culminated in this, the updated PET protocol for the SST.

Step-by-step protocol

Emphasized throughout this thesis are accurate diagnosis and thorough planning when considering PET. It is mandatory comprehensively examine the patient's general health, oral health status, treatment needs, absence of periodontal disease and/or extensive intrabony periodontal pockets, smile and facial analyses, prosthetic planning, etc. CBCT examination is also compulsory. The information is invaluable, informing the clinician of the radial plane root position within the alveolus, 3D bone availability, proximity to structures of risk, and so forth. From these CBCT views many critical factors need to be assessed, namely the anticipated SS dimensions in terms of root length and width, preparation direction, initial pilot osteotomy positioning, 3D implant positioning, prosthetic emergence profile, and the possible restoration retention options. Prior to the procedures, the tooth and site suitability should be assessed. Indications/ contraindications must be first be considered (Table S12). Once all these have been addressed and the SST selected, the following steps at the time of treatment apply:

1. Decoronation and endodontic post management

1.1. Measure the root length on the CBCT scan from the visible gingival margin to the root apex. (Technical note: The vestibule must be reflected during CBCT acquisition by retractor or cotton rolls to enable visualization of the soft tissue).

1.2. The same protocol for decoronating in the RST in section V.1.4 applies (Figs. 5a, b).

1.3. If a post is present it must be carefully removed. Use an irrigated high-speed handpiece coupled to a tapered diamond or root resection bur. The cut should not extend around the post fully. Instead cut first the root around post's palatal portion. This preserves the facial root portion. The cut is progressed slowly and apically in a sweeping motion, on the palatal side until the post loosens and it can be removed (or if securely bonded, to be cut away). Thereafter, conventional SS preparation steps can be followed.

2. Canal preparation and depth measurement

2.1. Widen the tooth canal with a number 1 Gates Glidden bur. This removes canal tissue /endodontic filling material if present (Fig. 5b). Then take a radiograph with the bur inserted to the apex to confirm the root length. (An endodontic file and apex locator are an alternative)

2.2. The canal is then widened further by successive increases in Gates Glidden bur size to the confirmed root length.

2.3. After the initial canal widening, a long-shank root-resection bur is marked with the root length and is rotated to depth directly down the root canal (Fig. 5c). (A lance bur with an adjustable depth stop may be ideal for this step)

2.4. Again, confirm with a periapical radiograph and ensure the apex has been reached. This confirms drilling within the canal has not deviated and is important to ensure that perforation or injury to adjacent roots and structures does not occur.

3. Sectioning the root

There is currently no consensus on the ideal SS dimensions in terms of length, thickness, etc. A thinner SS may be prone to fracture and mobility, especially if the implant and its threads exert force against it. It is also possible that contact between implant and SS is of no negative consequence. Nonetheless the current author recommends the facial root portion should be thicker, more robust and resilient to any forces. A larger, longer SS also means greater attachment via its PDL to BB, viz greater stability preventing mobility. Hürzeler & Baumer's working group had not specified a length. In the published diagrams the SS appears greater than a third and less than a half of the root length (137). This length may be adequate. However, if the majority of maxillary anterior roots are Class II (retroclined) (21), it would be unsafe to cut the root shorter to this length, whilst ensuring not to perforate the facial bone. It is unclear how it was possible to create this length of SS by the original protocol of drilling through the root with the implant osteotomy preparation drills and not perforate the facial bone. Apically however, the bone usually is more abundant, hence the current author suggests to section close to the apex whilst also removing it. This is achieved by enlarging the canal all the way to the apex, as described above. In this manner, an ideal approximate two thirds or greater of the root length can be prepared.

3.1. After enlarging the canal, section the root mesiodistally in a “sweeping” motion that progresses the root-resection bur apically. That is, advance the bur centrally down the canal, and then make “sweeping” motions carefully up that mesial or distal wall of the canal when exiting. Repeat these motions successively, until a mesio-distal slot is created in a C-shape (Fig. 5d). Also, roots are tapered and thus the range of mesiodistal motion should decrease apically so as to section the root rather than drilling into surrounding bone.

3.2. Once sectioning the root is considered complete, remove the lingual root portion by delivering it into the space created by sectioning (Fig. 5e). This is preferably done with a micro-periotome and elevator. Ensure finger pressure to support the facial root portion at the bony plate. Movement at the facial aspect may indicate incomplete sectioning of the root.

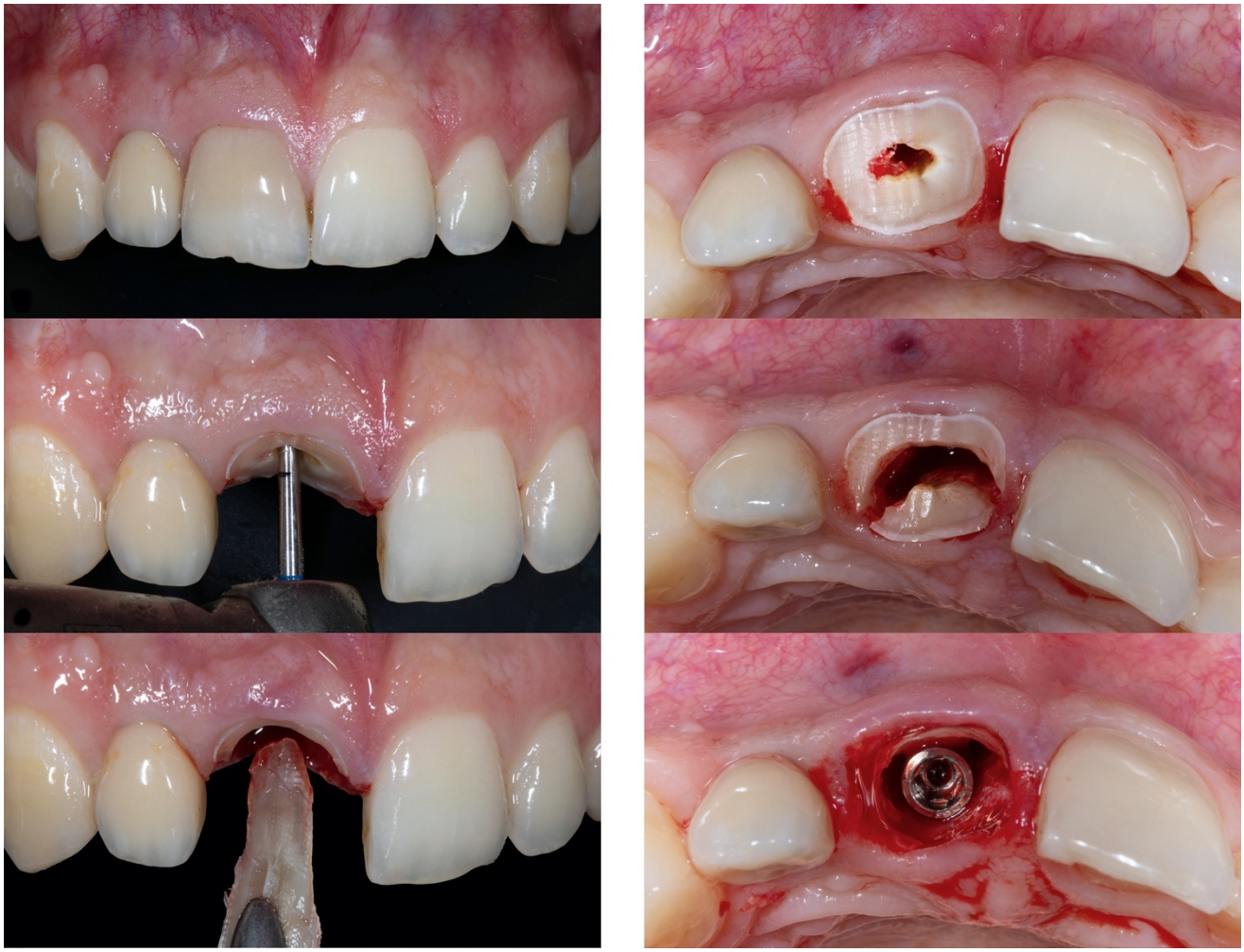
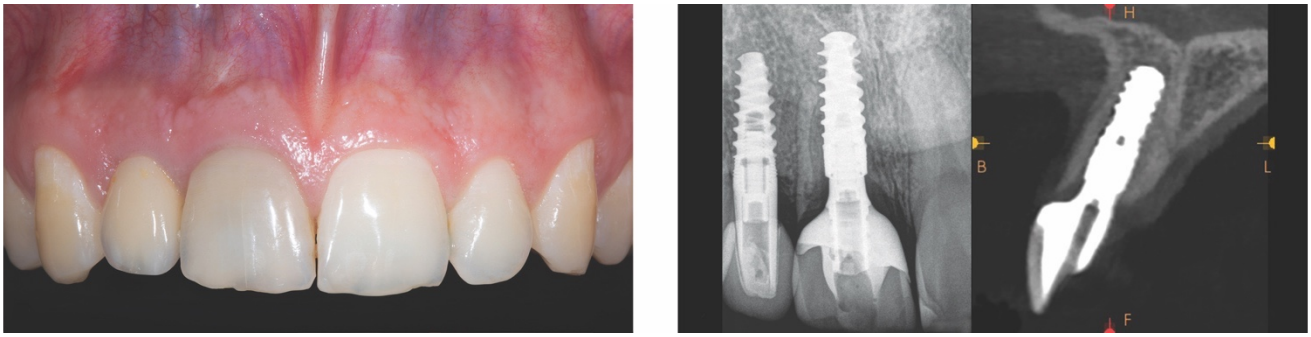


Figure 7: (a) Preoperative situation, tooth 11(#8) required extraction. (b) (top) Contra-angled handpiece with Gates Glidden bur, (below) straight handpiece with long-shank round diamond bur. (c) Tooth decoronated. Tooth had previous endodontic treatment (d) Radiographs. Confirmation of root. (e) Long-shank root-resection bur rotated to root apex, down widened canal. (f) Root sectioned mesiodistally, creating an arc. (g) Palatal root portion removed. Soft tissue reflected with gingival protector, socket shield reduced to bone crest. (h) Reduction started in the midfacial aspect, then levelled laterally to bone crest. (i) Implant inserted lingual to fully prepared socket shield. (j) Radiographs. Fully prepared socket shield left, implant with completed provisional crown right.



(k) The provisional crown at 11(#8), 1 year postop. (l) Radiographs. Note the bone at periapical view left. CBCT radial plane view right. (Proprietary images of Quintessence publishing, International Journal of Esthetic Dentistry)

4. Apical and inner root surface preparation

4.1. Once the lingual root portion is removed, the root apex (diseased or otherwise) and endodontic filling materials must be completely removed. This is verified by periapical radiograph. Radiopaque endodontic filling material, visible canal anatomy, and/or visible root apex on the radiograph require re-instrumentation with a bur for further removal. If the apex remains, it may be safely drilled away with the largest Densah bur that may fit into the socket apex. Next, the inner surface of the SS may be smoothed and shaped with a rounded, tapered diamond bur. Take care not to remove too much root tissue at this late stage. Though, there is no consensus as to the ideal SS thickness. Thickness of the SS is mainly dictated by the residual socket able to accommodate the immediate implant. As a general guideline, take care not to reduce more than half the distance from canal space to facial root surface (Fig. S16) (16).

4.2. Remove any apical pathology and infected tissues with socket curettes. Rinse the socket repeatedly with sterile saline.

5. Coronal root preparation

This part of the SST is discussed in great detail with its rationale hereafter in section V.2.4.2. Briefly described:

5.1. The SS should be reduced to bone level. Gently reflect the coronal gingiva and trim the coronal portion of the SS to bone level with an end-cutting bur (Fig. 6b). Magnification loupes and illumination are essential for these delicate steps. Take care not to cut and thin the facial soft tissue.

5.2. Next create an internal beveled chamfer of ± 2 mm. A large round diamond bur or other specialty bur would suffice.

5.3. Last, confirm the SS is firmly attached. Gently probe the inner dentin surface to confirm absence of mobility and take a periapical radiograph to ensure all the aforementioned steps are adhered to.

6. Implant placement

6.1. Implant osteotomy is then created apical and lingual to the fully prepared SS. Correct 3D restorative-planned placement is critical. Here some important factors require consideration. Where possible, ensure the implant is placed further from the SS toward the lingual, whilst always ensuring placement within the bony envelope (Fig. 5f). This is contrary to the original protocol of intentionally placing the implant in contact with it (15). A greater buccal gap allows space for adequate coronal soft tissue thickness and seal

around the implant prosthetic component. Furthermore, placing the implant in contact with the SS may unintentionally dislodge or even fracture it. Select an implant suited to IIP with an aggressive thread design, tapered implant body, platform-switched, and preferably a morse-taper-like connection implant.

6.2. Placement depth is also critical. This should be 1.5 mm below the facial bone crest and SS coronal limit (Fig. 7e). If placed too deep, limited bone may form between SS and implant. The SS coronal portion may have less support and be prone to fracture.

7. Management of the gap

7.1 Currently a single study has reported satisfactory clinical and radiographic outcomes after 1 year when the gap between implant and SS was not grafted (138). Grafting of this gap remains the clinician's prerogative until further data is generated. The current author recommends grafting this space, unless too small to accommodate the graft material. Bone or substitute material may prevent soft tissue ingrowth at the coronal aspect and help stabilize the blood clot to heal into bone. Using a rapidly substituting calcium phosphosilicate putty (Fig. 7f) may more accurately confirm bone infill on follow-up CBCT views (30).

8 Management of the gingival seal

8.1 The implant, SS, and bone graft within the gap must be protected from the oral cavity. At IIP a standard healing abutment by the manufacturer usually does not suffice. Constructing a customized healing abutment or an anatomical provisional crown is necessary. This is essential to support the original soft tissue profile, in keeping with the IIP protocol (47). Design of this prosthetic component is discussed in section V.2.4.2

This summarizes the PET protocol for the SST. IIP may always remain one of the most technically challenging procedures in dentistry, especially in the esthetic zone. The literature often states that IIP be reserved for the skilled and highly trained clinician (48). The current author would agree. Moreover, carrying out the SST requires detailed knowledge of the procedure and the possible pitfalls, the necessary instruments, anticipated complications, and so forth. Where then does the SS as a procedure fit in daily practice if it is an added challenge to immediate tooth replacement? Although a lot of improvements and recent knowledge pave the way for a wide dissemination of the SST, much remains yet unknown – the ideal size and dimensions, impact of the socket gap graft, the choice of bone material, whether bone will form to the most coronal limit of the SS toward the implant, etc. Nonetheless, whilst some questions may have been answered, it is clear that a high level of skill, experience, and training in implant dentistry are required for this treatment. This PET protocol should provide absolutely clear guidelines to follow.

V.3.2 Prosthetic management of the socket shield

The retrospective study published in 2017 might better be named "the complications report" (51). The reader would appreciate the frank disclosure of the article, divulging every detailed complication (Table 3). The overall complication rate was 19.5%. Among these, internal exposure of the SS through the overlying peri-implant

mucosa was the common (12/128; 9.4% of cases). This rate however was still remarkably low. The reader must ask do other publications provide in as much detail of all complications? And how do those equally minor complications compare in occurrence rate?

The exposures were the result of both prosthetic and SS preparation technique that required modification. In the original technique by Hürzeler and coworkers, the authors advocated preparing the SS above bone crest. In fact, their very first technique article was a bit confusing. In their animal experiment the "buccal fragment of the root was retained approximately 1 mm coronal to the buccal bone plate" and in the same article the patient case report was described as "[the] tooth was decoronated approximately 1 mm apical to the gingival margin" (15). These are certainly different heights to reduce the SS to. The reason for this supracrestal extension of the SS was not stated in the original technique article. In an identical technique reported 4 years after Hürzeler et al, authors Siormpas et al reported "the remaining tooth structure was leveled at no greater than 1 mm above the osseous crest" (134). Both those authors' techniques also advocated for drilling the implant osteotomy inside the tooth root. The PET protocol for preparing the SS does not. Instead, long shank root resection burs separate linearly, vertically, the facial and lingual root portions, drilling entirely separate from the implant osteotomy. Though, initially cases reported in the current author's retrospective study were also prepared to 1 mm above bone crest, as prescribed by Hürzeler et al. However, exposures sometimes occurred. To remedy this, a technique article was published (53). The PET protocol today prescribes reducing the SS to bone crest and not above it (Fig. 6) (55). The current author advises the use of an end cutting bur for this purpose (Fig. 7b). A flap should not be raised (unless multiple adjacent PET). Instead the soft tissue should be gently reflected using a gingival protector instrument.

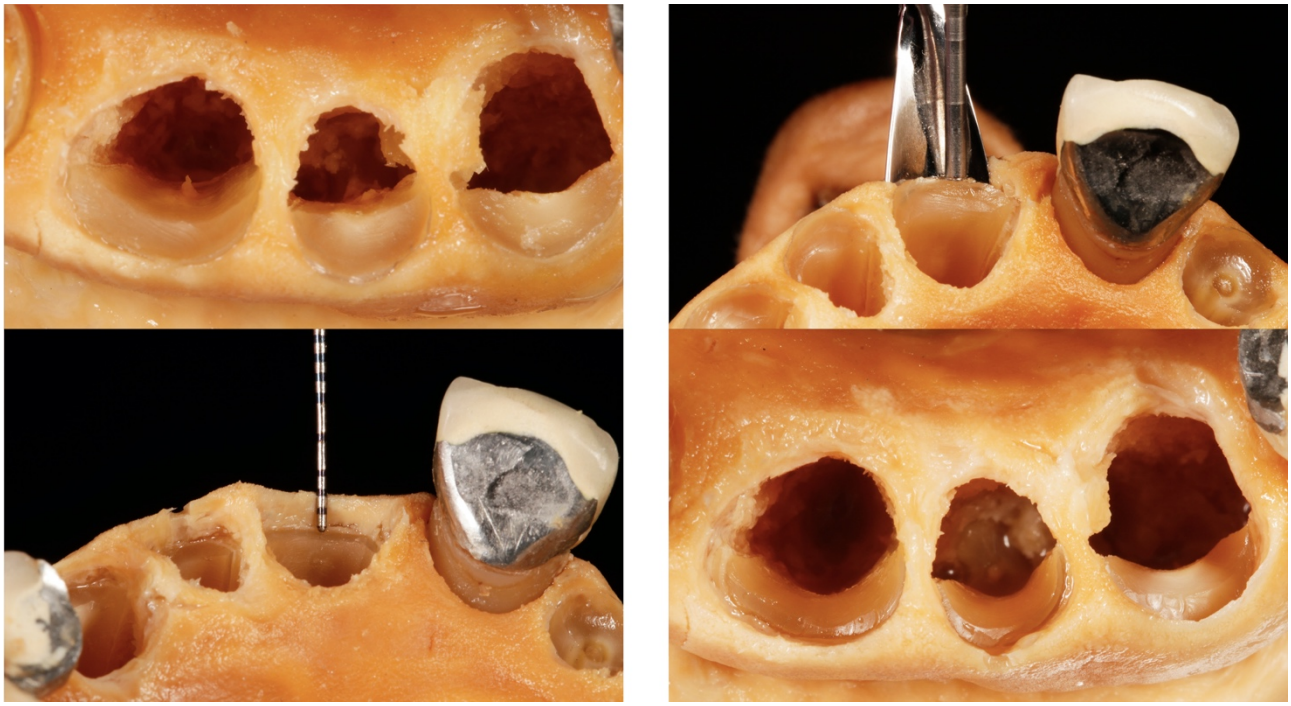


Figure 8: (a) Socket shields at gingival level after palatal root portions removed. (b) Gingival protector reflects soft tissue, end cutting bur reduces coronal socket shield to bone crest. (c) Coronal reduction complete. (d) Internal beveled chamfer complete.

Another possible cause of exposure is the prosthetic component's pressure against the SS. In conventional implant therapy, prosthetic pressure shapes the soft tissue whilst displacing it. At a SS, this hard tissue does not displace. Excessive pressure by a bulbous crown, or a SS overly large at its coronal aspect could cause an exposure. Thus, the PET protocol advocates reducing the coronal SS at its inner aspect into a beveled chamfer (Fig. 7d) Also, the emergence profile of the prosthetic component should be contoured into an S-shape (Fig. S17). Both these steps combined, create maximal space for soft tissue infill between the coronal SS and the abutment/crown, thus reducing exposures.

V.3.3 The molar socket shield

At the time of publishing this technique report in 2018, the SS had already been widely reported on (54). Though, none had reported on posterior sites. The posterior alveolar ridge is also susceptible to post-extraction collapse. Thus, preparing a molar tooth planned for extraction for both a Glocker technique and as molar SS is presented here (Figs. 10b, c).

In the current author's opinion the molar SS is certainly not suited to the novice clinician. Unlike anterior tooth roots, the roots of molar teeth can be excessively dilacerated and curved, making longitudinal sectioning of the root into facial and lingual portions a challenge. Also, complete removal of the apex is challenge. This part of the root at a SS cannot be left behind. Similarly the full removal of canal contents is difficult, even more so at tiny buccal roots of the upper molars. These are significantly smaller than most anterior roots. Also, the mesiobuccal root of upper molars typically has little to no buccal bone. There is a risk of perforating. This underpins the implicit need for CBCT examination when planning these cases. The current author argues that fused roots are the preferred teeth for molar SS. For lower molars the mesial root is typically the main challenge, being excessively curved.

The technique report outlined the preparation of an upper molar SS (54). The case presented in Fig. 10b is of an upper second molar with fused roots. Primary stability for IIP simultaneous to the SS was unlikely due to the insufficient apical bone. The site was thus planned for Glocker technique (section V.4). The same PET protocol was followed, since the roots were fused. The tooth was decoronated, the lingual and facial root portions separated. Lingual root portion was removed, buccal root portion was prepared into into a SS and reduced to bone crest (Fig. 10b). The ridge preservation achieved was clearly evidence, compared to adjacent full extraction sites enduring ridge collapse (Fig. 10c). At sites with bifurcated roots, both upper and lower, the clinician should ensure the principles of the PET protocol for SS are adhered to. The canal contents and the apices of the buccal root portions must be removed. The SS should be reduced to bone level. The prosthetic management may pose an additional problem. The furcation area and isthmus of tooth adjoining mesial and distal root portion may encroach on the implant, and not allow for adequate prosthetic space. Make sure to reduce sufficiently in this area to allow for adequate soft tissue infill, reducing the chance of later exposure.

V.3.4 The guided socket shield

The SST at IIP after 10 years has made tremendous inroads into implant dentistry, supported by a wealth of literature, practiced the world over. However, IIP in the correct 3D position to be restored, with sufficient primary stability to support a provisional restoration, or at least a customized healing abutment, is already a very difficult sequence of techniques to execute correctly. The added preparation of a SS significantly increases the overall difficulty. The published technique reports specify preparation requirements (16, 55). Among these, the root should be sectioned along its long axis, separating facial from lingual portions. The SS should be large enough to ensure a sturdy periodontal attachment. It should not be too short, to avoid risk of mobility and migration. The full root apex may not remain and this portion must be removed. The socket and adjacent structures should not be damaged during the root resection. These requirements are difficult to satisfy, since a long-shank bur is inserted into the tooth root within its socket, with the clinician essentially working blind. These aspects may be the single greatest obstacle to even wider adoption of the technique. A guide that could overcome these and better ensure accuracy, safety, and ease of treatment, would therefore be of great benefit.

A pre-clinical study was carried out in a series of cadaver jaws with the aim of successfully preparing SS via a fully, static-guided root resection method (61). The measurable objectives for a "successfully prepared SS" are outlined in Table S13. The study was carried out in accordance with the statement of ethical principles for medical research as laid out by the World Medical Association Declaration of Helsinki. Prior to commencing, the protocol was first reviewed and approved by the Faculty of Health Sciences Research Ethics Committee at the University of Pretoria (registration number 476/2018). 10 cadaver jaws were secured for testing the prototype guides. Digital impressions were taken and combined with CBCT scan data to design a surgical guide in an implant guide planning software (Codiagnostix, Dental Wings Inc.). The digital files were loaded in the software such that the surface topography of the teeth and soft tissues were orientated accurately with the 3D radiographic imaging. The SS dimensions were planned according to the previous published PET protocol (Fig 7a). The tooth planned for extraction was located in the software, and viewed first in the radial plane. This oriented the root vertically within its bony envelope. The trajectories to section the root in relation to the limits of the bone were then planned. As stated, established requirements for preparing the SS include complete removal of the root apex and its canal contents. In the software, trajectories were planned such that the customized long-shank root resection burs converged on the apex to cut away this part of the root. The planning was then viewed in the horizontal plane, to ensure the correct facio-lingual positioning of these virtual cutting trajectories. These were positioned to cut the root in a concaved "C" shape from mesial to distal (Fig. 7c). From bone crest to apex, the radial and horizontal planes were viewed repeatedly to adjust and confirm the correct 3D positioning of the root resection trajectories. It is the current authors opinion that the SS should be as long as possible whilst still fully removing the apex, and as thick as reasonably possible whilst removal all canal contents, also providing adequate space for the implant placement. The guided software ensures the resection burs are fixed and secure in their cutting trajectory paths, whilst also safely preventing drilling beyond the apex. Contrary to previous published protocols of drilling the implant osteotomy inside the root, the root's long axis rarely corresponds to the correct

3D positioning of an implant. This is especially true if the restoration is screw-retained, requiring the implant be far more retroclined, to position the screw access on the lingual aspect of the restoration. Once the planning was complete, a guide was 3D printed in resin. At mock surgery on the cadaver jaw, the guide was positioned and correct seating confirmed via the guide "windows" and tooth crowns positioned within these (Fig. 7b). For the guide to seat correctly, the tooth crown at the planned SS was first removed. Decoronation was carried out as described in section IV.1.3. Peri-apical radiographs and CBCT views were taken at multiple stages during the procedures.

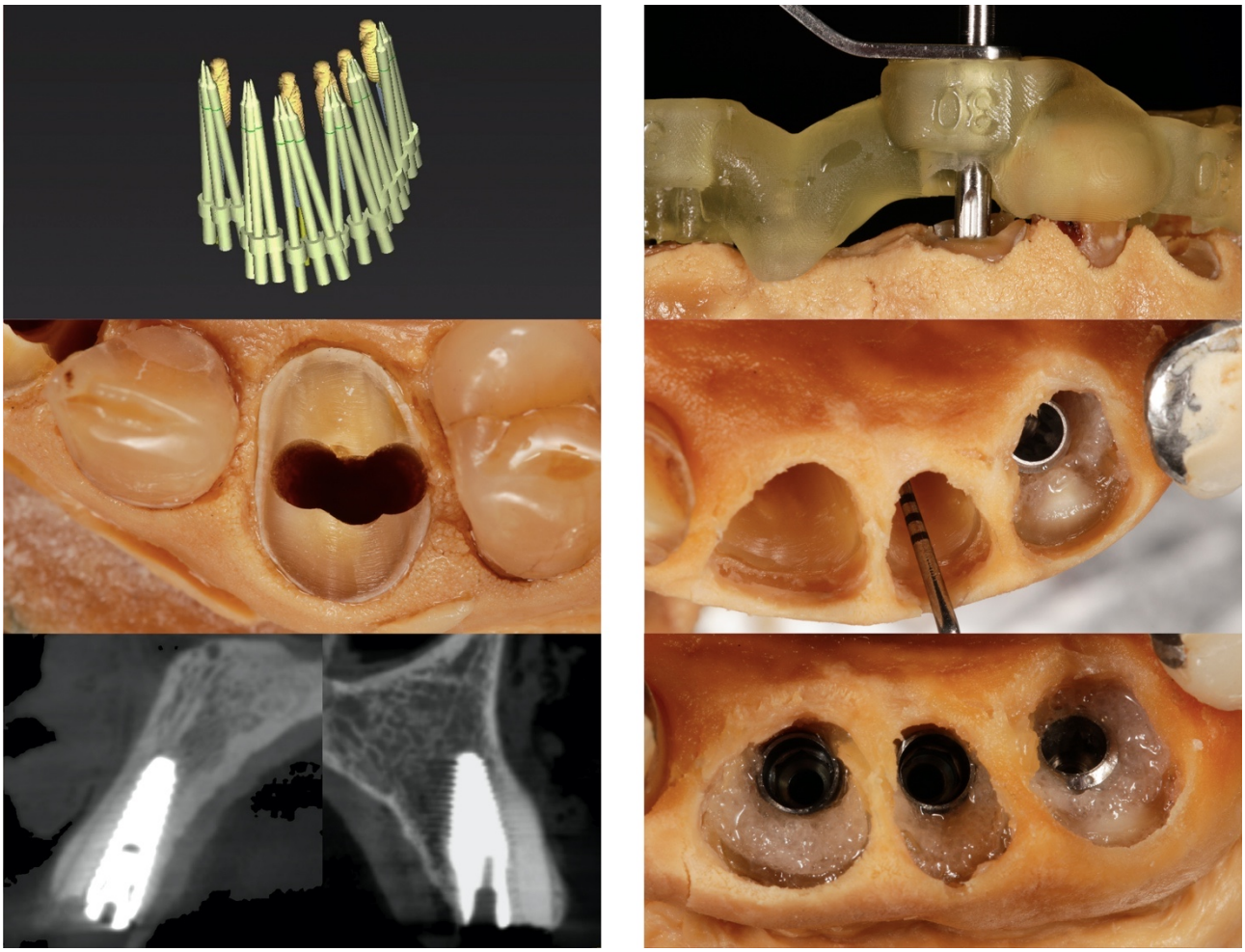


Figure 9: Guided socket shield. (a) Software planning of root resection bur trajectories, in relation to planned implant position. (b) Root resection bur positioned in guide. (c) Initial sectioning of root via guide. (c) Fully prepared socket shields, 1 implant in position. (d) Final CBCT images of completed socket shields sites 22 and 23 (#10#11), implants placed lingual. (e) Final step, buccal gap between socket shields and implants grafted.

With the guide positioned and secured with finger pressure, the customized bur was inserted through the guide to contact with the decoronated root surface. With adequate, cooled surgical irrigation, at about 1200 RPM, trajectories were cut through the root to its apex. Firm pressure was applied to advance the bur, at increments of 1-2 seconds only, and repeatedly withdrawn to allow for cooling and removal of the dentin debris. The planned vertical offset of the guide allowed for a safety stop, ensuring the root apex was reached, and drilling far beyond it was prevented. Drilling was repeated for 3-4 trajectories down the root's long axis, these trajectories

overlapping, separating facial from lingual root portion. However, more often than not, minor additional sectioning of the root was required to fully separate these two portions, separating the isthmus of root between facial and lingual portions. The guide was removed and these final cuts made with a long-shank root resection bur coupled to an irrigated high-speed handpiece. The subsequent steps then were identical for the conventional PET protocol for SS preparation, as per section IV.2.4.1 (Figs. 7d-f). CBCT radiographic data was evaluated after removal of the lingual root portion and before any final preparations/adjustments of the SS (Fig. 7e). These 3D images were compared to preoperative dimensions of the planned SS to assess the validity of the guided approach, according to the prescribed measurable objectives (Table S13). The singular objective #4 was assessed clinically.

Results

During this study several different prototypes of a guide to section the root and prepare a SS were developed (Fig. S18). It is of paramount importance to report the failed results, such that other investigators do not waste time on similar failed approaches, and to best ensure safety of the procedure for patients. Guide prototype 1 was designed to have a slot, positioned in a C-shape, through which a conventional root resection bur was hypothesized to section the tooth root. This guide however provided no support to prevent excessively tipping the rotary instrument in all axial directions. Only a vertical stop at the midpoint of the root, if cut directly apically, could possibly ensure accuracy at this point only. A false sense of security was provided at all other aspects, unsafe to the patient. Guide prototype 2 modified the same slot, to have a second wider slot, in which a rotary instrument stopper was planned to be positioned while cutting. This better ensured the rotary instrument did not excessively tip in a facio-lingual axis, but was not sufficiently stable in a mesio-distal axis. Also, this guide could not control the variable depths to correctly cut a tapered root – shallower mesial and distal, and deepest at the root apex midpoint. Guide prototype 3 planned for a round stopper on the shank of the rotary instrument, and for this round stopper to run in a U-shape within a corresponding slot in the guide, such that the guide could predict the variable depth of cut from mesial to distal. However such a guide could only have single, flat, vertical interface, and could not provide sufficient stability to the rotary instrument. Guide prototype 4 utilized a totally different concept. Multiple overlapping implant pilot holes, if positioned along the root's long axis to converge at the root apex, and spaced mesio-distally in a "C"-shape, were hypothesized to section the root. The failure with this guide was materials related. Printing a guide out of resin did not allow for sufficient material thickness and strength. These guides easily fractured. Guide prototype 5 was designed, with the offsets greatly increased, such that the converging pilot holes were farther spaced to better ensure material thickness. Custom long-shank burs were made to ensure the cutting flutes did not engage the guide's holes. Alas, these still engaged, and the guides easily fractured. Guide prototype 6 was printed in titanium to overcome the strength issues of the resin guides. A longer rotary instrument was used, with a combination of a 3-sided lance tip and spiraling, cutting flutes. This guide was a hit and miss. The guide provided superior strength, better restricting the rotary instrument in its cutting trajectories. The friction with the guide produced titanium particles dispersed over the tissues. Ultimately, the cutting flutes locked into the guide's channels, bending the rotary instrument irreparably. Guide prototype 7 combined the lessons learned from the previous designs, to return to a basic

design of a resin-printed guide, with a metal sleeve-key insert to provide stability and accuracy. Customized long-shank burs corresponded to these inserts, with minimal tolerance to ensure little to no deviation along the cutting trajectory. In the cadaver model, 8 consecutive SS were successfully prepared according to the prescribed criteria (Table S13). That is, by using the guide roots were safely and accurately sectioned into facial and lingual root portions that enabled successful preparation of SS adjacent to implants.

V.3.5 Pontic shield technique

Socket grafting has been argued in this thesis as being insufficiently effective at prevent post-extraction ridge collapse. Submerging a root is arguably the ideal ridge preservation procedure and for preparing pontic sites. Though, as described in detail in section V.1.4, roots with endodontic pathology require treatment prior to submerging. Furthermore, areas of larger apical destruction may have poor prognoses, requiring time to first observe endodontic treatment outcomes. Consider also that not all clinicians routinely provide endodontic treatment. Referral for multidisciplinary management thus increases cost and duration of treatment. Instead, combining a SS with conventional socket grafting is a viable alternative, viz the pontic-shield technique (PST) (Figs. 10d, e) (52). The added benefit is should a root planned for submergence intraoperatively present with a necrosed pulp/endodontic pathology, one can promptly opt for the pontic-shield technique if endodontic treatment cannot be immediately provided.

To demonstrate this, the current author published in 2016 on 14 PST in 10 patients. The approach was identical to the PET protocol for the SST. Comprehensive patient assessment was implicit, particularly CBCT examination. Apical pathology may progress to the facial aspect of a root. Viewing this in the radial plane on CBCT and then planning to manage it are essential. There are options. Either the root needs to be sectioned shorter to create sufficient space after removal of the palatal portion to adequately debride the area. Or an additional apicoectomy can be carried out. Emphasized here is the debridement of the apical socket. In the 14 PS reported on, the sockets were thoroughly debrided to ensure complete removal of any pathology. Both large and small sized socket curettes were used, whilst rinsing with sterile saline repeatedly. After the meticulous cleaning, all sockets were grafted with a collagenated xenogeneic bone particulate (Gen-Os, Osteobiol). Any socket grafting material may suffice. The current author would argue that a non-collegenated, sintered xenograft that is slow/non-resorbing is ideal. These sites are planned to receive tooth pontics. The aim is not to regenerate bone to receive dental implants. The aim to maintain maximal ridge volume (Fig. 10e). Final closure of the PS sites was variably managed: CTG, socket seal surgery, dPTFE membrane, buccal advanced flap, and no closure. The results confirmed that these sites require closure to avoid exposure of the PS a FGG/CTG is necessary. This additionally provides soft tissue bulk for an ovate pontic of the prosthesis to develop. Subjective ridge preservation was noted at all 14 PS sites. The study was limited by not assessing these objectively. Future volumetric and CBCT studies will hopefully include these measurable objectives, and possibly a control arm (conventional socket grafting) for comparison. To conclude, the PST is a legitimate PET with value to both patient and clinician.

V.3.6 The Glocker technique (delayed socket shield)

In 2014, Glocker et al described a delayed socket shield (143). The first part of the treatment is identical to the PST in section V.3 above. The only difference may be the choice of socket graft material. A non-resorbing bone substitute is not ideal, since the implant is planned to be placed into that material. Autogenous bone, allograft, or a fast-substituting synthetic material would be preferable. Once the site is fully healed, it is re-entered and an implant is placed (Fig. 10a). This is an essential part of PET. Consider sites treated as a ridge preservation, and then receiving an implant at a later date. SST is the first choice, but consider also sites with extensive apical pathology. These may need to heal first. Consider sites that fail to gain primary stability, or for whatever reason that the implant cannot be placed as planned on the day.

V.3.7 Molar root resection

As this thesis draws to an end, this is the last PET to report. Multirooted teeth and furcation areas are prone to periodontal disease. Severe attachment loss at a single root and not at others of the same tooth, pose a challenge (Fig. 10f). To eliminate the intrabony defect(s), the furcation area, whilst also capitalizing on the retained attachment of the other roots, such a molar tooth root may be resected. The technique has been described for decades, with phenomenal success reported. For example, in a recent study by Derks et al, 90 molar teeth had ailing roots resected and were reported at up to 30-years follow-up (12). The survival rate of these molars at 10 years was an astounding 90.6 %, and 80 % at 20 years. As such, MRR is an evidence-based PET with proven benefit.

Brief technical notes on MRR commence again with diagnostics emphasized. Radiography and probing depths would confirm a molar root with severe attachment loss. In lieu full extraction, the tooth may have endodontic treatment, the offending root section free and removed. The remaining crown is supported by the remaining roots. There are options with regards to site of resection, and restoration. The root may be sectioned from its root trunk only, without removing any of the crown (Figs. 10g, h). Some may argue the occlusal forces may inappropriate and the crown too should be sectioned. Others yet may argue the full crown may create a retention area for bacterial plaque. The clinician may use their own discretion. Ideally the root area sectioned and exposed to periodontal tissues should be sealed with a bioactive endodontic cement. If possible, the furcation area widened or removed. At removal of the sectioned roots, the bony defect may be augmented. If done with care, MRR may afford the patient years of molar function yet.

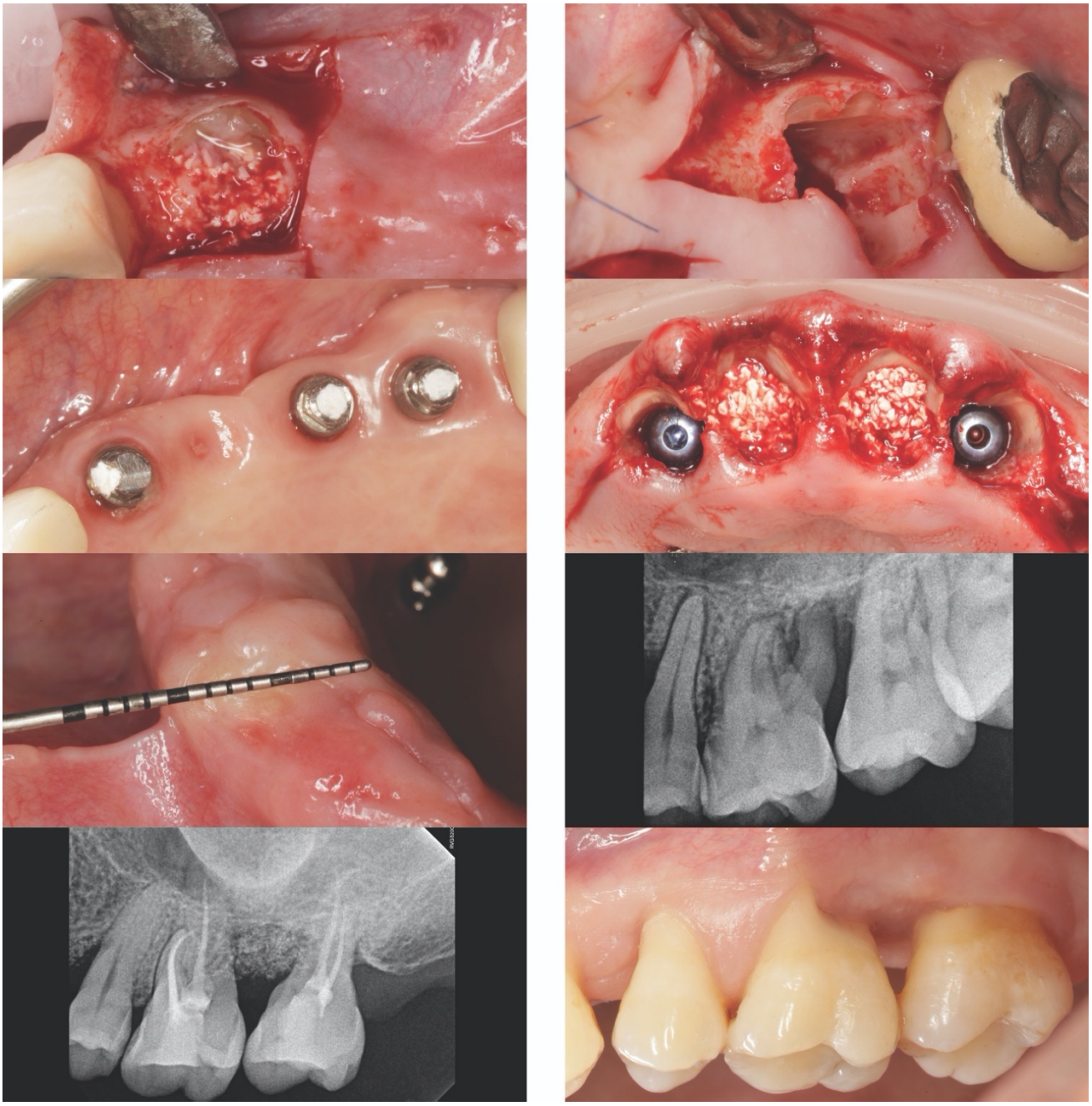


Figure 10: Multiple PET. Case 1, (a) Healed Glocker technique at upper canine site, (b) molar SS prepared in the same patient, (c) healed implants receiving restorations. Note the buccal contour at canine and molar sites, versus adjacent extraction sites. Case 2, (d) pontic shields at upper central incisors, (e) after healing. Case 3: (g) severe bone loss due to periodontitis. (h) Distobuccal root of 1st molar and mesiobuccal root of 2nd molar resected, defect grafted, radiograph and (h) clinical photo at 2-years postop.

VI. DISCUSSION

A memoir of one's life's work and research could afford a discussion. Where does such a discussion fit in a thesis limited to 50 pages? Though, what more can be said that has not already in the previous five sections of this thesis? What more convincing is necessary to argue that preserving the patient's own tooth and ridge tissues should take preference to invasive extraction and augmentation. To quote Alessandro Devigus, "minimally invasive dentistry is the application of a systematic respect for the original tissue" (144). Is prevention then not better than cure? The PET all prescribe to this single concept of ridge preservation, of conservative dentistry over invasive treatments. The RST and MRR date back more than 50 years. At a decade of literature reports and worldwide clinical application, the SST now too is no longer experimental. There are 4, 5, 6-year data reported. The technique has been carefully improved over the past 10 years. There are volumetric data, micro-CT data. There are large patient cohorts of > 100 reported. Retrospective studies, prospective studies, RCT, and numerous case series' are reported. Several studies have provided both human and animal histology. We are long surpassed questions such "do these techniques work?". Now we must ask how can they work better?

VII. CONCLUSIONS

In reading this thesis to its conclusion, the reader should be convinced that one technique does not supersede another. Patients are not to be treated epidemiologically. The main duty of the clinician is to practice evidence-based treatment, and when appropriate, select the treatment best suited to that patient in that situation. The partial extraction therapies have been firmly established today within the implant and restorative dentistry milieu. These treatments underpin a conservative approach to patients, recognizing that an artefact is of less biological value than the original healthy tissue. May these ever evolve for the better of our profession and management of our patients.

VIII. NEW FINDINGS

1. Our CBCT studies showed that the anterior maxilla in most patients is <8 mm. If attempting ridge preservation by socket grafting, a repeat augmentation will usually be necessary.
2. Our second CBT study also showed the facial bone plate is usually <1 mm. This bone is prone to resorption and a challenge to immediate implant placement.
3. Our published textbook chapters addressed augmentation materials and techniques, their details and shortfalls. The histology study in humans showed PRF does not improve bone healing.
4. Thereafter, we published the largest retrospective study of 128 socket shield cases. The results showed that implant survival rate was comparable to conventional implant treatment.

5. The human and animal histological data we published confirmed bone can grow between implant and socket shield. The latter study confirmed that a thicker, longer socket shield, with internal beveled chamfer is a better preparation.
6. Our subsequent technique articles published consecutively on improved methods. The prosthetic management article addressed the issue of socket shield exposure. The molar socket shield article introduced the treatment at posterior sites. The pontic shield technique provided an alternative to root submergence with apical pathology.
7. Finally, a 2-year study experimenting on several prototypes for a guided socket shield technique was reported with promising results.

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APPENDICES