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Surgical repair of root and tooth perforations

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A root perforation is a mechanical or pathological communication formed between the supporting periodontal apparatus of the tooth and the root canal system. Three broad categories of etiological factors exist and these are procedural mishaps, resorption and caries. The diagnosis, management and repair of root perforations require skill and creative thinking. Unfortunately, much of what has been written on the subject of root perforation repair is unsubstantiated and empirical in nature and contributes little to evidence-based support for any specific repair procedure. However, perforation repair frequently provides a very attractive and frequently successful alternative to extraction of the involved tooth. In recent years, the procedure has become more predictable owing to the development of new materials, techniques and procedures.

Introduction

A root perforation is a mechanical or pathological communication formed between the supporting periodontal apparatus of the tooth and the root canal system (1). Perforations result in the destruction of the dentine root wall or floor along with the investing cementum. This communication compromises the health of the periradicular tissues and threatens the viability of the tooth (2–7). In a recent outcomes study (8), a group in Toronto found that in retreatment cases only two factors affected the success rate of the treatment significantly: (1) the presence of a preoperative radiolucency and (2) the presence of a preoperative perforation.

Perforations are regarded as serious complications in dental practice and pose a number of diagnostic and management problems (9). However, when teeth are of strategic importance perforation repair is clearly indicated whenever possible (10). Unfortunately, however, there is a paucity of evidence-based research upon which treatment decisions can be based.

Traditionally, the presence of radicular perforations has been both difficult to determine and manage (11–13). Most frequently, they were managed surgically, but in recent years non-surgical correction (14) of many perforations has been facilitated by the use of improved magnification and illumination provided by the use of loupes or the surgical operating microscope (SOM) (9, 10, 15–28). In practice, however, the indications for surgical correction of root perforations are being eroded from two directions: on the one hand by the improved non-surgical management of perforations and on the other by the use of implants.

Perforations occur primarily through three possible mechanisms: procedural errors occurring during root canal treatment or post-space preparation (29, 30) (Fig. 1A, B), resorptive processes (31) (Fig. 1C, D) and caries (Fig. 1E). Most perforations result from procedural errors (32, 33). Errors leading to these defects include bur perforation during access opening or during the search for canal orifices, excessive removal of dentine in the danger zone (32, 34–42), either with hand or rotary instruments (Fig. 2A), misdirected files during canal negotiation, unsuccessful attempts at bypassing separated instruments (Fig. 2B) and misaligned instruments during post-space preparation (25, 43–48).

Resorption is either a physiologic or a pathologic process resulting in loss of dentine, cementum and sometimes bone (1). In terms of establishing a treatment plan, it can be classified as external, internal

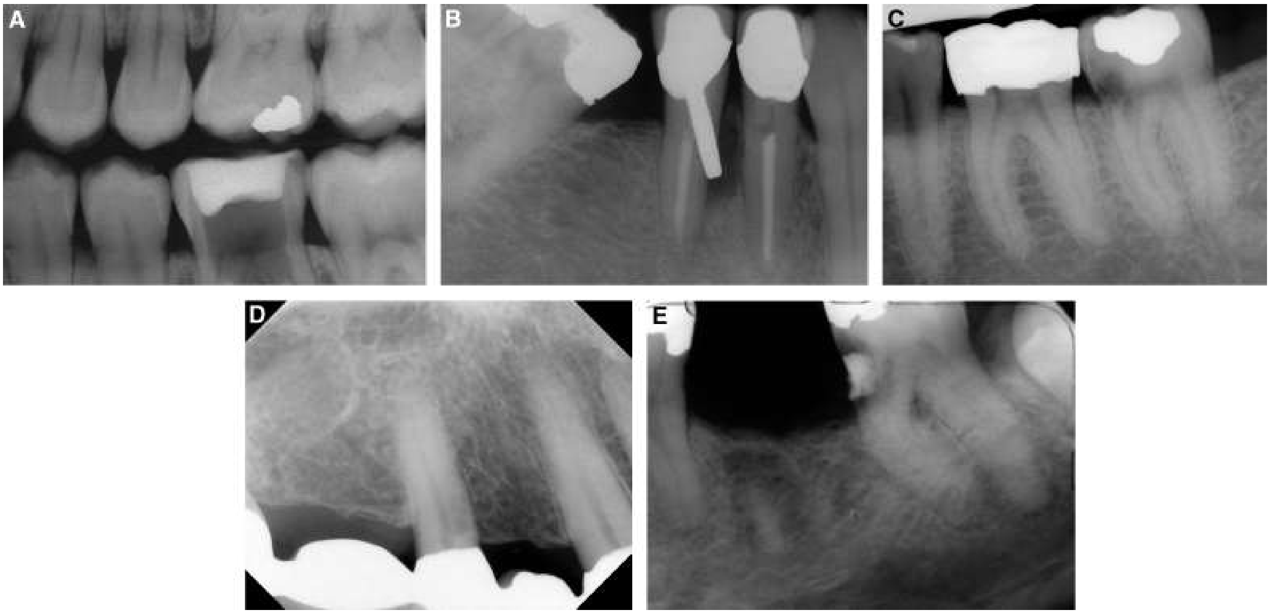

Fig. 1. (A) Furcation perforation following misguided access preparation. (B) Mandibular premolar root perforation by misaligned post placement. (C and D) Resorptive processes resulting in root perforation. (E) Carious destruction resulting in perforation of the root from the external into the pulp canal space.

or cervical as these frequently necessitate different approaches or a combined approach. Resorption is a perplexing problem for all practitioners. Diagnosis is frequently complicated by the lack of radiographic evidence until extensive demineralization has occurred (49, 50).

Unmanaged carious lesions can proceed to perforation or near-perforation in the cervical region of the tooth, at or below the level of the crestal bone (2, 51, 52). This is particularly common in older patients where salivary quality and quantity is diminished and gingival recession has led to dentine exposure.

Management of perforations will depend on a number of factors, including:

- diagnosis,
- etiology,
- location of the perforation,
- access to the perforation site,
- visibility,
- adjacent anatomical structures (including adjacent roots),
- perforation size,
- periodontal status,
- time lapse since the creation of the perforation,
- strategic importance of the tooth and
- experience of the operator.

Diagnosis

As time lapse between the creation of a perforation and its repair is critical to the prognosis for the tooth (53, 54), early and accurate determination of the presence of a perforation is of paramount importance (2). The etiology for a perforation will play a major role in determining the management protocol. A diagnosis is established based on clinical and radiographic assessment. At times, it is immediately apparent, either clinically or radiographically, or both, that a perforation has either been created or exists (Fig. 1C, D). However, it is frequently difficult to determine the presence or location of a perforation and careful consideration of all diagnostic information is essential. Radiographs from multiple angles, including bitewing radiographs, will dramatically improve the clinicians diagnostic acuity (55, 56) (Fig. 3A, B). This is especially evident when trying to assess the location of the defect, particularly when it is located either buccally or lingually, as the image of the defect is often superimposed on that of the root (57).

The apex locator, normally used to determine canal working length, is an invaluable instrument in confirming the presence of a perforation when other clinical indicators are inconclusive (58, 59). This is especially true during access preparation or during the search for a

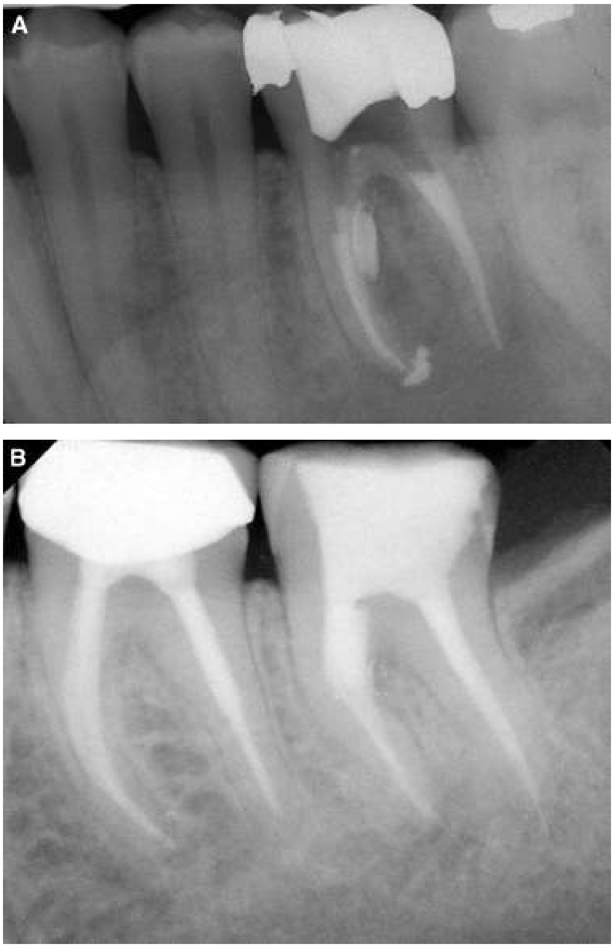

Fig. 2. Perforations resulting from procedural errors. (A) Excessive dentin removal from the 'danger zone' resulting in strip perforation of the mesial root of this mandibular molar. (B) Excessive dentin removal during attempt to remove separated instrument resulting in perforation of the root.

canal orifice. The use of the apex locator will provide the clinician with an early warning of the existence of a perforation and may prevent further extension of the defect or the extrusion of obturating materials or irrigating solutions into the defect (Fig. 2A).

Fig. 3. (A and B) Radiographs from multiple angles, including bitewing radiographs, will facilitate diagnosis of pre-existing perforations.

Etiology

As mentioned previously, root perforations can be classified into three main groups: procedural errors, tooth resorption and caries.

Procedural errors

Procedural errors can occur at any stage during endodontic treatment and are very likely to influence the prognosis for the tooth (2, 14, 28, 60–63). Coupled with an aging population and an increased demand to retain their natural dentition, patients are receiving more complex dental treatment (54, 64). Consequently, clinicians are treating increasingly more difficult endodontic cases, which in turn is associated with a greater occurrence of procedural errors (54, 64). Iatrogenic perforation of the tooth may occur during access preparation, canal instrumentation or during the creation of post-space prior to definitive restoration of the tooth (Fig. 4A, B). The perforation may be the

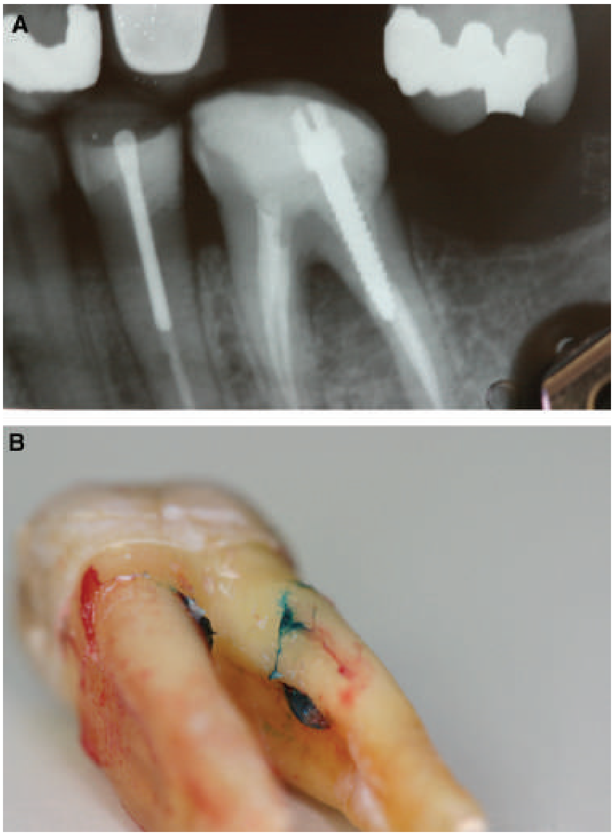

Fig. 4. (A) Radiographic appearance of post-perforation. (B) Clinical appearance of extracted tooth showing post-perforation in the concavity in the distal root of a mandibular molar.

result of a lack of attention or experience on the part of the clinician or may result from an attempt to locate a pulp chamber or canal orifice or to negotiate a calcified canal system.

Perforations may also result from excessive removal of tooth structure during instrumentation of the canal system and this tends to occur in anatomically vulnerable locations such as the danger zones on the mesial roots of lower molars (32, 35). In all cases, prevention is preferable to cure and is facilitated by a thorough knowledge of the anatomy of the tooth and by careful assessment of the available radiographic and clinical information prior to treatment (65). The physical dimensions of an iatrogenic perforation will be determined in part by the instrument that created it. Typically, perforations formed in the floor of the chamber with a round bur tend to be large and circular. On the other hand, perforations formed during preparation of a post-space tend to be elliptical and large. Perforations caused by an endodontic instrument during negotiation of a canal system tend to be smaller and relate to the particular diameter of the last instrument used.

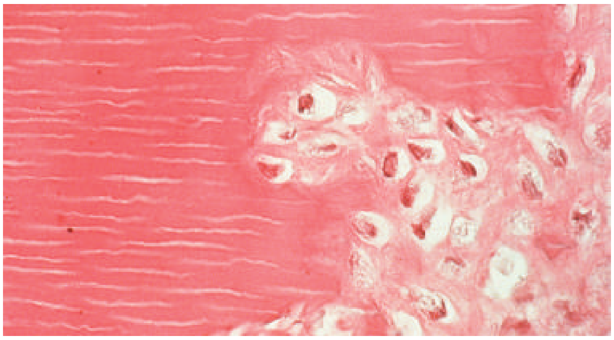

Fig. 5. Clastic cells resorbing dentine. The mineralized tissue of the tooth does not normally undergo resorption.

Tooth resorption

The mineralized tissue of the tooth does not normally undergo resorption. The actual reason for this is not entirely understood, but a number of theories have been proposed to explain the resistance of the tooth tissue to clastic cellular activity (Fig. 5). Firstly, it is believed that the root is protected by the remnants of Herthwig's epithelial root sheath that surrounds the root in a mesh-like manner (66). The second hypothesis suggests that the non-mineralized covering of the dentine provided by pre-dentine internally or the external cementoid layer externally provides the protection (67). The clastic cells require the presence of extracellular proteins containing the aginine–glycine–aspartic acid (RGD) sequence of amino acids for binding (68–77). The RGD sequence is missing in these non-mineralized layers. The third hypothesis suggests that the pre-dentine and cementoid layer contain an intrinsic factor osteoprotegrin (OPG) that inhibits osteoclastic activity (78–83).

Resorption is most frequently categorized into discrete entities, either internal or external, and guidelines leading to the systematic differential diagnosis have been described in detail (84). Frank (13) suggested that internal resorption is the result of external resorption that has progressed to internal involvement. However, most authorities now agree that internal resorption is a discrete entity. While the pathogenesis of internal resorption is not fully understood, it is more easily managed than external resorptive defects provided that the process has not led to perforation of the root. On the other hand, external root resorption demands more complex treatment, which is in turn determined by the site, nature and extent of the lesion. External root resorption can be classified according to the site, nature and pattern of the process. Many different classifications (7, 85–87) have been proposed. Those suggested by Ne et al. (88) includes, *External Surface Resorption, External Inflammatory Root Resorption, Ankylosis and External Replacement Resorption.*

Caries

The carious process involves destruction of dental tissues as a result of microbial action (1). An untreated carious lesion may invade the floor of the pulp chamber or extend along the root, resulting in perforation of the root. Treatment of these perforations may require a combination of crown lengthening, root extrusion (surgical or orthodontic) or tooth/root resection in order to retain valuable radicular segments (2, 89–93).

Location of the perforation

When treatment planning for perforation repair, the location of the perforation is probably the most important and overriding factor in the decision-making process. Fuss & Trope (7) presented a classification that emphasized the relationship of the perforation site to the 'critical crestal zone.' This classification divides the root into *coronal*, *crestal* and *apical* portions: *coronal* being defined as 'coronal to the crestal bone and epithelial attachment'; *crestal* being defined as 'at the level of the epithelial attachment and crestal bone' and *apical* being defined as 'apical to the crestal bone and epithelial attachment.' In addition to considering the position of the perforation in relation to the 'critical crestal zone,' its position in the mesial distal and facial lingual planes must also be taken into account (2, 57, 61).

Non-surgical treatment is indicated, whenever possible, in the management of perforations. Surgical intervention is reserved for cases not amenable to, or which have not responded to, non-surgical treatment, or in which the concomitant management of the periodontium is indicated (57). There is no clear-cut distinction between those cases that are best treated non-surgically and those treated surgically, and, frequently, creative combinations of both non-surgical and surgical approaches must be adopted. The decision to repair perforations surgically can only be made when a number of considerations have been addressed. These considerations include the following:

Will access and visibility be adequate?
Can adjacent structures be protected?
Will the perforation repair result in the creation of an untreatable periodontal defect?

Management of individual perforation scenarios relative to the location of the perforation will be discussed later in this article.

Access and visibility to the perforation

Access and visibility are determined, in the main, by the location of the perforation. Irrespective of the location relative to the critical crestal zone, the location of the perforation relative to the horizontal axis of the tooth will greatly influence its management. Buccally placed perforations (Fig. 6) are invariably easier to manage than those located lingually or proximally, and consequently afford a more varied opportunity for repair; this will in turn favor a surgical approach (2, 57, 63, 94, 95). Lingually located defects, especially in the mandible,

Fig. 6. Buccally placed perforations are invariably easier to manage than those located lingually or proximally. (courtesy of Dr J He, Dallas, TX, USA).

frequently exclude the surgical option (57) and are either managed non-surgically, orthodontically or, alternatively, the tooth may be destined for extraction.

The introduction of improved illumination and magnification provided by the SOM has been beneficial in the management of perforations both surgically and non-surgically (17–20, 22, 23, 96–98). In fact, many cases are now managed non-surgically that previously would have had a very poor surgical prognosis (Figs 1B and 7). While many perforations of iatrogenic or carious origin have well-defined limits, those owing to resorption frequently undermine the radicular tissue in all dimensions and are difficult to visualize or to determine the extent of their boundaries. Unless the boundaries of a perforation can be adequately visualized, accessed and isolated, repair becomes difficult if not impossible (49, 99).

Adjacent anatomical structures

Protection of adjacent anatomical structures is a major consideration when planning to repair a perforation surgically. The anatomical structures most likely to be damaged include adjacent radicular structures, neural structures, the maxillary sinus and the soft tissue of the reflected tissue flap. Location, identification and isolation of the structures will usually prevent long-term permanent damage during the surgical procedure (57, 100, 101).

Management of perforations

Gutmann & Harrison (57) reported in the classic surgical text, Surgical Endodontics, that the surgical repair of perforations has received sporadic attention in the dental literature and has been supported primarily by case reports or limited studies (33). Since then, little has changed and the surgical management of root perforations continues to be a poorly understood and executed endodontic procedure. As with all surgical specialties, the endodontic clinician must possess a thorough understanding of the anatomy and physiology of the oral soft tissues, osseous tissues and tissues that comprise the periodontium (57).

Perforation size, interval as the defect was created and periodontal status are factors that have major influences on the prognosis for success (2, 5, 7, 14, 20, 25, 28, 29, 61, 62, 102–105). These will be discussed in the overall discussion on surgical management of the perforation defect. As discussed by Weine (106), management of perforations demands ‘spontaneity and creative approaches.’ The management of the perforation will be discussed in terms of the critical crestal concept as described above (7).

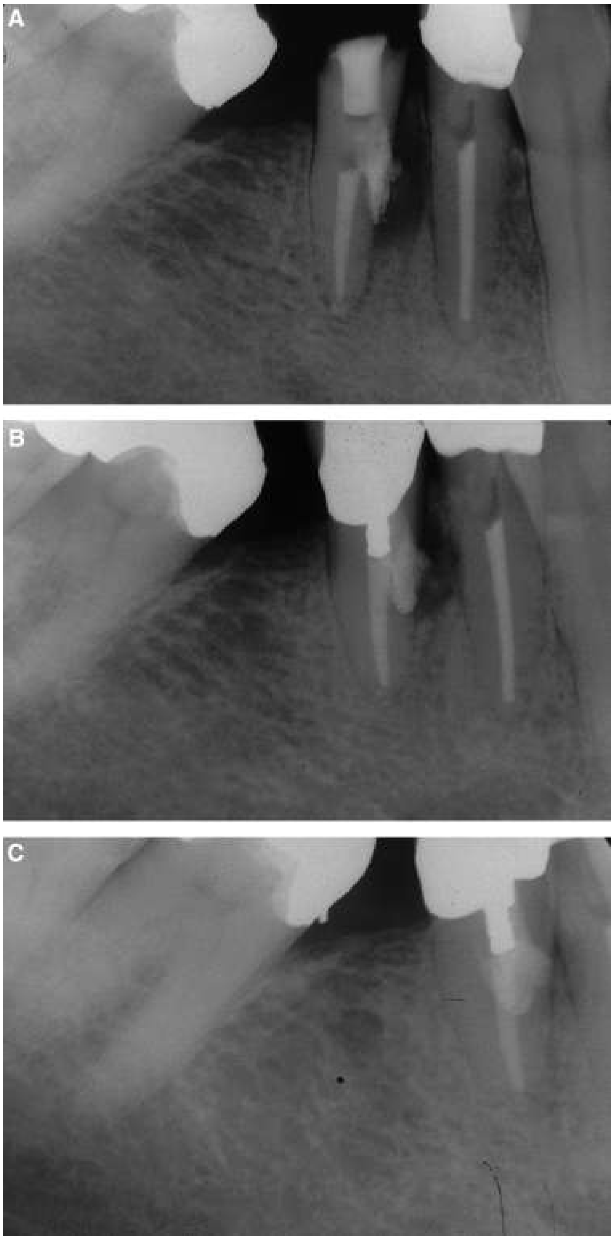

Fig. 7. (A) Internal approach to repair of post-perforation of mesiolingual aspect of the root of a mandibular premolar (see Fig 1B). (B) Retreated tooth and definitive restoration of tooth. (C) Two-year follow-up of tooth.

Supracrestal perforations

Perforations coronal to the crestal bone can frequently be managed non-surgically. The perforation can usually be repaired with standard restorative materials such as amalgam, gold, composite or cast metal restorations. The margins of cast restorations can be extended so as to include the defect. In order to facilitate the repair, it may be necessary, at times, to extrude the tooth orthodontically to a point where the perforation defect becomes supragingival and unlikely to impinge on the biologic width. (Biologic width denotes the combined connective tissue and epithelial attachment from the crest of the alveolar bone to the base of the gingival sulcus.) (1, 92, 93, 107–111) Alternatively, the defect may be exposed surgically or the tooth may be intentionally replanted surgically following repair of the perforation defect (112, 113).

Surgical crown lengthening may be indicated or used to assist in the surgical access to coronal-third root perforations, especially when the subgingival defect can be transformed into a supragingival defect (114–120). A minimum of 4 mm of sound tooth structure must be exposed by the surgical procedure (116, 117, 119, 121). Four millimeters corresponds to the measurement from the bony crest to the edge of the sound tooth structure and includes a minimum of 2 mm for ‘biologic width’ (122). Biologic width is the amount of space required for health by the gingival tissues (1.07 mm connective tissue attachment and 0.97 mm junctional epithelium) and was first reported by Gargiulo et al. (123) working on cadavers. In addition, they found the average sulcus depth to be 0.69 mm. This measurement of 2 mm is an average for biologic width that varies among patients (124) and even among sites in the same patient.

If a restoration violates this space below the base of the sulcus, it will result in inflammation of the tissues. How the gingival tissues respond to a biologic width violation depends on tissue ‘biotype’ (125–127). Patients with a thick ‘biotype,’ which is thick gingiva and thick bone, will demonstrate persistent inflammation unless the biologic width re-establishes itself and the probing depth around the tooth deepens as a result of this inflammation-induced bone resorption. A moat-like crater may form in the bone around the tooth if it is very thick. A patient with a thin biotype will respond to biologic width violation by gingival recession and bone resorption.

To determine if crown lengthening is a practical solution to managing a perforation, it is important to consider the anatomical relationship to the adjacent teeth and their supporting tissues. The bone supporting the adjacent teeth will also require recontouring if the formation of a bony step is to be avoided. If a bony step is created during the surgical procedure, the gingiva will proliferate coronally instead of remaining at the new, planned, more apical position. In addition, teeth with subgingival restorations and narrow zones of keratinized gingiva have statistically significant higher gingival scores (plaque and bleeding) than teeth with submarginal restorations and wide zones of keratinized gingiva (128, 129). Therefore, if a tooth already has little keratinized tissue (less than 2 mm), it is important to aim to preserve this during surgery (130). In the molar area, the length of the root trunk must be taken into consideration because a tooth with a short root trunk is more likely to have furcation involvement as a result of the surgery than a tooth with a medium or long root trunk.

Crown lengthening may be performed either by using a simple gingivectomy technique that will sacrifice attached gingiva and not permit any bone contouring or surgically reflecting tissue and performing an ostectomy and/or osteoplasty. If no bone is removed, care must be taken to ensure that there will be enough biologic width space created or the gingival margin will creep back towards its original position, resulting in a ‘shortening’ of the clinical crown (128, 129).

Following administration of anesthesia, the surgical procedure is initiated by placing a reverse bevel incision at the crest of the free gingiva to the gingival attachment extending from the mid-labial aspect of the adjacent teeth. It is important to maintain as much attached gingiva as possible. The resected tissue lining the sulcus and the interproximal tissue is then curetted. A second incision is made running parallel to the surface of the gingival tissues from the crest of the gingival tissue to the bone. The second wedge of tissue is removed with the curette. The tissue can now be retracted as an envelope flap. In most cases, vertical-releasing incisions will not be required and should in fact be avoided if possible to facilitate repositioning of the reflected tissue. Bone can be removed with chisels (such as Wiedelstadt chisel) or burs. End-cutting friction grip burs are very effective instruments and can be used safely without damaging adjacent tooth structure. Alternatively, a no. 6 or 8 round burs can be used to thin the bone sufficiently so that the chisel can then be used. The bony contours should follow a smooth path into the interproximal areas avoiding the creation of sharp ledges or grooves. Following completion of the bone removal and osseous recontouring, the flap is positioned apically and sutured into place. Periodontal dressings such as Coe-Pak are placed routinely to provide protection for the healing tissues and reduce discomfort for the patient (131).

Apical third perforations

Perforations in the apical third of the root can be considered simply as an extra exit from the canal system and managed either non-surgically or surgically (2, 95, 99). If the defect cannot be managed non-surgically, resection of the root apex is usually the most efficacious method for repair provided that the crown–root ratio remains favorable. These types of perforation include apical perforation of the root during instrumentation of the canal system or placement of a post, perforation following zipping of the apical portion of the canal, deviation of the root canal instrument during cleaning and shaping or in an attempt to bypass an obstruction in the canal system. Perforations in the apical portion of the root rarely communicate with the oral cavity and are therefore not exposed to constant microbial contamination (62).

Critical crestal zone perforations

Perforations in the 'critical crestal zone' are invariably associated with a less favorable outcome and are frequently more difficult to manage (2, 7, 132). These perforations are most susceptible to epithelial migration and rapid periodontal pocket formation (133, 134). Management of the repair of these defects will depend on many factors. Those necessitating surgical intervention include the following:

- Perforations in areas not accessible by non-surgical means alone.
- Perforations of the root with a concomitant periodontal component.
- Perforations that have not responded favorably to non-surgical repair.
- Extensive defects that provide no physical boundaries against which to apply repair material.
- Perforations of a root that require a separate apical surgical procedure.
- Perforations owing to resorptive activity not easily managed from within the canal system.
- Defects into which excessive amounts of a foreign body, such as obturating material, has been extruded.

Surgical management of perforation defects

The aim of surgical perforation repair should be to produce an environment conducive to the regeneration of the periodontium (28, 132, 135, 136). Periodontal tissue reactions to experimentally induced perforations in animals (137, 138) and accidental perforations in humans (5, 139–141) have been studied. Successful regeneration of the periodontal tissue will return the tooth to an asymptomatic functioning unit of the dentition (142–145).

Three broad categories of crestal zone perforation defects exist that can potentially be repaired surgically. These are:

(1) *Strip perforations*: Complete penetration of a root canal wall owing to excessive lateral tooth structure removal during canal preparation (6, 48, 103, 146).
(2) *Furcation perforation*: A mechanical or pathological communication between the root canal system and the external tooth surface and occurs in the anatomic area of a multi-rooted tooth where the roots diverge (6, 26, 34, 35, 137, 147–154); and
(3) *Perforations related to external cervical root resorption*: A relatively uncommon, insidious and often aggressive form of external root resorption, which may occur in any tooth in the permanent dentition (13, 87, 88, 155–160) (Fig. 1D, E; see Fig. 14B).

Ideally, furcation and strip perforations should initially be managed using a non-surgical technique. This approach will preserve the periodontium, thus increasing the probability of long-term success. Only when disease persists should surgical management of strip and furcation perforations be considered.

On the other hand, management of external cervical root resorption ideally should be managed from an external approach while attempting to maintain pulpal viability if at all possible. Only when the pulp is already irreversibly inflamed or necrotic, or when removal of the diseased dentine tissue unavoidably causes irreversible pulpal injury, should a root canal procedure be performed. With this in mind, the management of category I and II external cervical root resorption defects as described by Heithersay (159) should be approached from the external or periodontal structure. Management of category III (Heithersay) resorptive defects can be attempted by either an internal or external approach depending on which procedure produces the least amount of tooth and periodontal destruction. Category IV defects are deemed unrestorable. The external approach to the management of cervical root resorption has been achieved using two techniques: (1) a chemical cauterization of the lesion using 90% trichloroacetic acid (159, 161, 162) and (2) surgical removal of the lesion (2, 14, 61, 62, 94, 132, 134, 142, 147, 163–169). The discussion in this paper will be limited to surgical management. For the sake of discussion, the surgical repair of any perforation defect can be broken into soft-and hard-tissue management even though they are clinically inseparable.

Soft-tissue management during surgical repair of perforation defects

The basic window for soft-tissue access is similar for each type of perforative defect with slight modifications introduced as necessary to accommodate the surgeon's need in managing the underlying hard tissues. In designing the soft-tissue access window, several factors must be taken into consideration including frenal and muscle attachments, bony eminences and the position of the defect itself (57, 170, 171). The soft-tissue access window is formed by combining a horizontal relieving incision and if necessary vertical relieving incision(s). Given that the defect is frequently close to the marginal tissues, a vertical relieving incision may not be required or if required may not need to extend to the depth of the vestibule. As with periradicular surgery, vertically orientated relieving incision will limit the number of vessels severed (172, 173) diminishing the potential for hemorrhage, which is especially critical if bonded materials are planned for the restoration of the defect.

Horizontal relieving incision

In view of the fact that a defect may extend interproximally, the only appropriate form of horizontal relieving incision in the region of the tooth being treated is one where the entire dental papilla is completely mobilized. Thus, the horizontal intrasulcular incision should extend from the gingival sulcus through the periodontal ligament fibers and terminate at the crestal bone and pass adjacent to each tooth (57, 128, 129, 174, 175). Occasionally, when a defect extends interproximally, the tissue is reflected on both the lingual and buccal sides of the tooth. As the horizontal relieving incision extends beyond the tooth with the defect, other forms of intrasulcular incisions such as the papillary-base incision (176–178) can be used.

Vertical relieving incision

If a vertical relieving incision is required to improve access to the defect, several general principles should be followed. The incision should be parallel to the long axis of the tooth where possible and should not involve frenae, muscle attachments or bony eminences unless necessary. The incision should be made over healthy bone distant from the site of the defect, beginning at the midpoint between the dental papilla and the horizontal aspect of the buccal gingival sulcus, thereby avoiding dissection of the dental papilla (57, 129, 174).

Soft-tissue access window design

Combinations of vertical and horizontal incisions are used to achieve various soft-tissue access window designs. A full mucoperiosteal reflection is required, lifting the entire body of soft tissue as one unit, including the alveolar mucosa, the gingival tissues and periosteum. Three variations of soft-tissue access window can thus be established (57, 171, 179, 180):

- *Limited triangular*: One vertical relieving incision (see Fig. 10B).
- *Limited rectangular*: Two vertical relieving incisions.
- *Envelope*: No vertical relieving incision (see Fig. 14D).

Tissue reflection

Elevation and reflection of the entire mucoperiosteal complex are essential and will help to minimize hemorrhage during the procedure (181). If a vertical relieving incision is used, tissue elevation and reflection should begin from this vertical incision within the attached gingivae (57, 100, 174, 182). However, if a horizontal incision alone is used, then elevation and reflection should begin at the region of the diseased

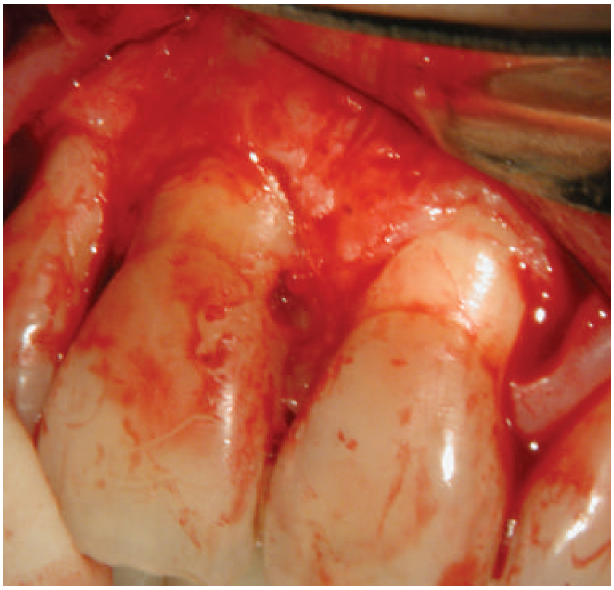

Fig. 8. Design of the surgical flap to allow for tissue over teeth adjacent to the tooth with the defect to be reflected. This will provide for good access and visibility.

tissues. Once the tissue adjacent to the defect has been elevated, the surgeon should use a gentle rocking motion to continue the elevation and reflection in a mesial and distal direction as required (57). Typically, the tissue should be reflected to include teeth adjacent to the tooth with the defect (Fig. 8). Defects that involve the furcation and mid-root region will require either a limited triangular or limited rectangular soft-tissue access window.

As the underlying bone of the cortical plate is undulating (183) (Fig. 9), damage to the fragile soft tissues during elevation should be avoided. The surgeon should take great care to prevent slipping of the elevator during the tissue reflection; this can be achieved by using an appropriate instrument that is stabilized with adequate finger support. As the interdental papilla is approached, a narrower instrument may be required to gently undermine and elevate the tissue in this region. This process should be continued gradually until the osseous tissues overlying the diseased tooth structure are adequately exposed.

Once the tissue is elevated, it must be retracted to provide adequate access for management of damaged radicular tissues. The main goal of tissue retraction is to provide a clear view of the bony surgical site and to prevent further soft-tissue trauma (57). When a horizontal incision alone is used, the major concern during elevation and retraction of the tissue is avoidance of tearing or crushing of the tissue. A tear will usually occur at the point of maximum tension where the tissue is being retracted most (174, 182). This occurs most frequently in close proximity to the defect and a tear in the tissue in this region can complicate wound closure. The surgeon should therefore carefully consider the use of a simple envelope access window.

Fig. 9. As the underlying bone of the cortical plate undulates, care must be exercised to avoid damaging the fragile soft tissues during elevation (courtesy of Dr JL Gutmann, Dallas, TX, USA).

Hard-tissue management

As with any surgical procedure involving bone, the aim should be to remove the affected tissues, conserve the healthy hard tissue and to minimize heat generation during the process (57). Similar to root-end surgery, hard-tissue management involves five phases. Firstly, removal of healthy tissue to gain access to the diseased tissues followed by removal of the diseased tissues and foreign material. These two phases are then followed by the third stage, which is the formation of an appropriate cavity form to receive the restorative material. The fourth phase of the process aims to achieve a dry surgical field using appropriate hemostatic techniques and materials (181) followed by placement of the restorative material in the cavity. Finally, in the fifth phase, the root surface is conditioned (184, 185), if appropriate, prior to tissue re-approximation. Typically, a surgical high-speed bur is used in phase one and two of the procedure. As the need for a greater refinement of the perforation site increases and the space in which to achieve this refinement decreases,

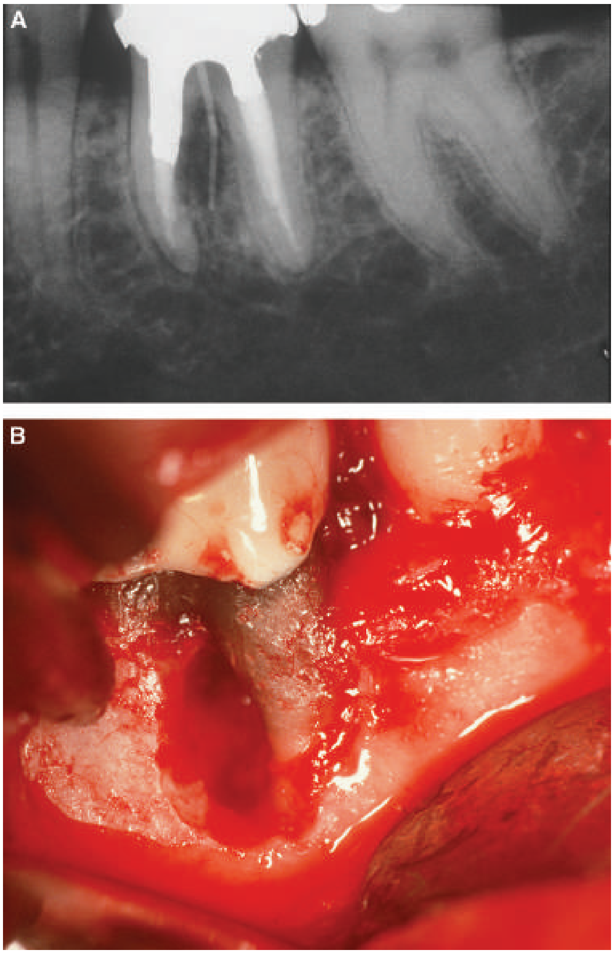

Fig. 10. (A) Radiographic image showing strip perforation. (B) Associated bone destruction exposed following reflection of overlying soft tissues.

ultrasonically energized tips can be used in phases two and three. It is useful to have a wide array of ultrasonic tips available during the surgical procedure, as the various clinical scenarios that may arise are not often easily managed using a single ultrasonic tip.

Hard-tissue management: furcation and strip perforation

These defects (Fig. 10A, B) have similarities with the conditions found in periradicular surgery. There is a typically a region of persistent disease associated with an iatrogenic defect. This leads to a bacterial-stimulated growth of granulomatous tissue and associated bony loss (186–196). The goals of the surgical procedure are to debridé and then seal the defect to prevent further egress of microorganisms from the canal system or from the oral cavity into the periradicular tissues (57). Thus, the surgeon may view this procedure as simply a root-end surgery carried out in a different region of the tooth. The management of such a defect thus requires the same systematic approach as that used in root-end surgery. If the lesion perforates the cortical plate, then the soft tissue should first be peeled away from the osseous crypt, starting at the lateral borders. This can be accomplished efficiently by using the curette with the concave surface facing the internal envelop of the osseous opening. Once the soft-tissue lesion has been separated from the bone to the point where the crypt changes its convexity, the curette can be used in a scraping manner to remove the remainder of the granulomatous tissue from the opposing wall of the osseous defect (57, 101, 179, 197, 198). If the cortical plate is intact, then a hard-tissue access window can be made using a multi-fluted round bur in a rear vented high-speed hand piece (199) applying copious sterile irrigation. This combination in conjunction with an effective irrigation system reduces the heat generated in the bony crypt (200–206). Temperature increases above normal body temperature have been shown to be detrimental to the osseous tissue (207–222). The surgeon should collate information gleaned from multiple radiographs, clinical examination and knowledge of the relevant tooth anatomy to establish the most appropriate access point to the defect. Once the lesion proper is entered and the access window expanded sufficiently, the soft-tissue lesion can be removed as described previously. Having removed the lesion, the focus of the procedure is now to identify and clean the perforation. As with root-end surgery, an appropriate ultrasonic root-end preparation tip can be used to clean and simultaneously establish a cavity form. The use of the SOM in conjunction with microsurgical instruments and mirrors greatly facilitate this procedure (20, 163). As this type of perforative defect is typically encased in bone, the material of choice to restore this type of defect is mineral trioxide aggregate (MTA).

Hard-tissue management: cervical root resorption

In order to manage this type of defect properly, it is important to understand the clinical nature and appearance of cervical root resorption. Clinically, the lesion that forms adjacent to cervical root resorption can vary from a small defect at the gingival margin

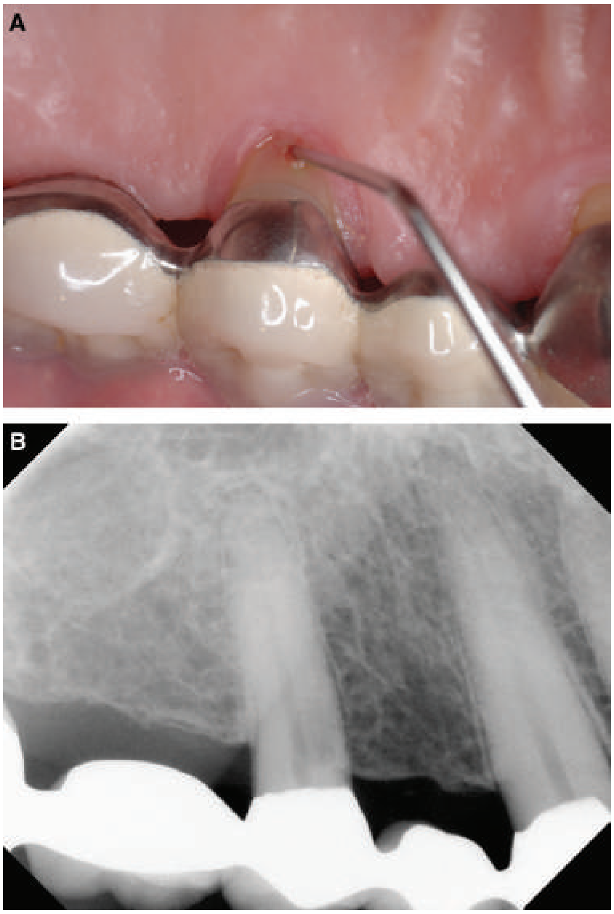

Fig. 11. (A and B) Resorptive processes frequently begin as small defects at or below the gingival margin. As shown in the radiograph, the lesion appear to progress by penetrating deep into the dentin structure of the tooth through small channels initially. These channels gradually become enlarged and contain fibro-osseous tissue.

(Heithersay Class I) to extensive undermining cavitations of the tooth enamel that produces a pink coronal discoloration of the tooth crown (49). The resorbing tissue is fibro-vascular in nature with odontoclastic cells adjacent to the dentine surface. The lesion appears to progress by penetrating deep into the dentine structure of the tooth through small channels initially (Fig. 11A, B). These channels gradually become enlarged and contain fibro-osseous tissue. An overlying inflammatory response can be present when a secondary invasion of microorganisms occurs.

Successful surgical intervention requires that the entire pathological process be eliminated. (A diagrammatic representation of these procedures is illustrated in Fig. 12.) The use of magnification and powerful illumination can enhance the ability of the surgeon to visualize the diseased tissues and thus ensure adequate removal. The basic principle is to use a small instrument to remove the ingrowths of fibro-osseous tissue (49, 99) into the dentine and preserve the dentine where it is normal. Several different types of burs are useful in removing resorptive tissue. These include slow-speed burs such as the Müller bur, the LN bur and round #1 surgical length latch burs. High-speed surgical length round #1 bur can also be used but require a greater degree of control owing to their superior cutting ability. Diamond-coated ball and pear-tipped ultrasonic instruments are also useful, both to remove small increments of bone and affected dentine (223–225). Once all of the diseased tooth structure has been removed, the tooth needs too be thoroughly examined to assess the viability of the pulp. If the long-term integrity of the pulp is compromised or a pulpal exposure is present, then non-surgical root canal treatment is indicated. If rubber dam isolation can be established (Figs 12E–G and 13), performing root canal treatment through the existing defect, if possible, can prevent further destruction of the tooth. An ultrasonic root-end preparation tip can be used to clean the pulp chamber proper. If adequate isolation cannot be established, then the defect should be restored first and the non-surgical root canal treatment completed subsequently. The integrity and patency of the pulpal space can be maintained by placing a gutta-percha cone in the canal itself. This will prevent the restorative material from flowing into and occluding the canal system (Fig. 12F). As aesthetics are frequently important in this type of perforative defect, a bonded tooth-colored restorative material that is tissue 'friendly' to the gingivae is most appropriate (Fig. 14). An alternative is to reposition the flap apically to the base of the resorption repair. Should this be aesthetically unacceptable, orthodontic extrusion can be used to improve the gingival contour (109, 114, 226).

Hard-tissue management temperature changes

Temperature increases above normal body temperature within osseous tissues have been shown to be detrimental (207, 214–217, 222). A round bur used with a gentle brush stroke action has been shown to prevent rapid increase in temperature of the bone and produces a wound site with less inflammation (200, 201, 204–207). The use of a coolant during bone cutting is essential, as the absence of an appropriate irrigant can

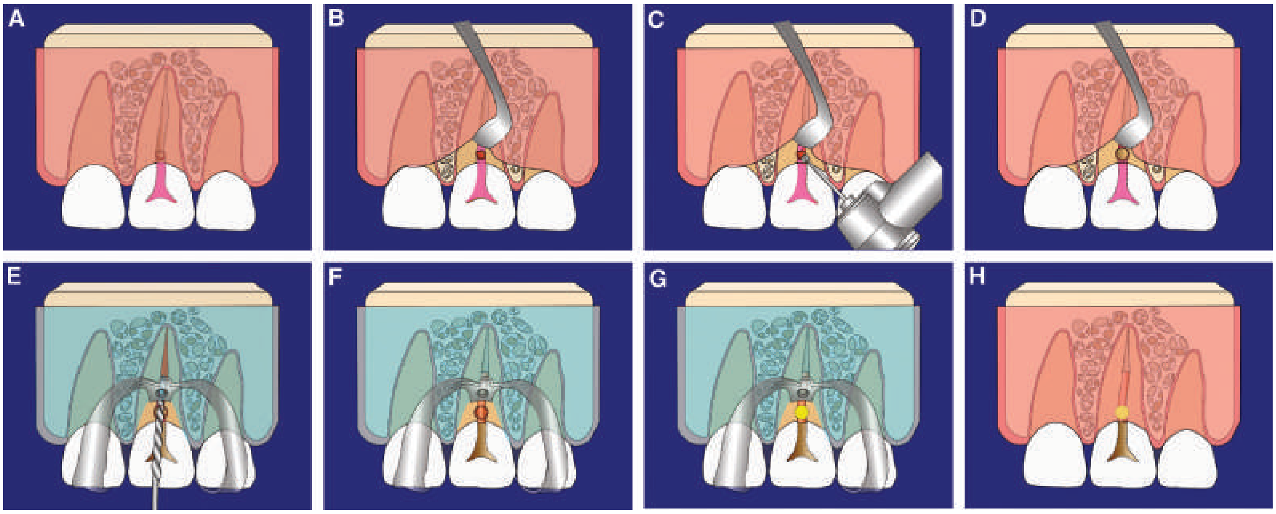

Fig. 12. Diagrams demonstrating techniques for the management of a resorptive perforating defect of the root of a maxillary central incisor. (A) Radiographic image of perforating defect. (B) Reflection of tissue where an envelope tissue flap design has been used. (C) Use of rotary instrumentation to remove the fibrous-osseous tissue and to prepare the root for a restoration. (D) Completed preparation. (E) Placement of dental dam and root canal system debridement. (F) Temporary occlusion of the canal system with a gutta-percha cone and restoration of perforation defect. The gutta-percha cone prevents blockage of the root canal system by the restorative material used in restoration of the perforation defect. (G) Completed root perforation repair. (H) Replaced soft tissue flap.

Fig. 13. Clinical example of dental dam isolation of perforation defect prior to restoration with composite restorative material.

result in temperature increases in excess of those known to impair bone healing (227). Temperatures can rise above 100°C by applying excess pressure during cutting, by burying the bur into the bone, or where little or no irrigant reaches the cutting tip (206).

All ultrasonic surgical tips should contain an irrigation port. Using an ultrasonic instrument in the wound without adequate irrigation can also result in an extreme temperature increase within the tissues, although this specific effect has not been demonstrated during endodontic surgery. However, the effect of scaling without irrigation produces an increase in dentine temperature of up to 35°C above baseline temperatures (228). This increase in temperature during scaling and root planning was described as being injurious to pulpal and periodontal tissues (228, 229). Recently, the use of non-cooled ultrasonic instruments within the canal system has been cited as the cause of extensive thermal injury to the periodontium (230).

Placement of the restorative material: localized hemostasis

Localized hemostasis throughout the surgical procedure, particularly during placement of the restorative material, is essential to ensure the successful repair of the perforating defect. Good hemostasis will minimize surgical time, blood loss, postoperative hemorrhage and swelling (57). Hemostatic agents used during endodontic surgery are intended to control bleeding from small blood vessels or capillaries. Localized hemorrhage control enhances visibility and facilitates assessment of root structure and ensures establishment of a dry environment for the placement of restorative materials. Several agents have been advocated to

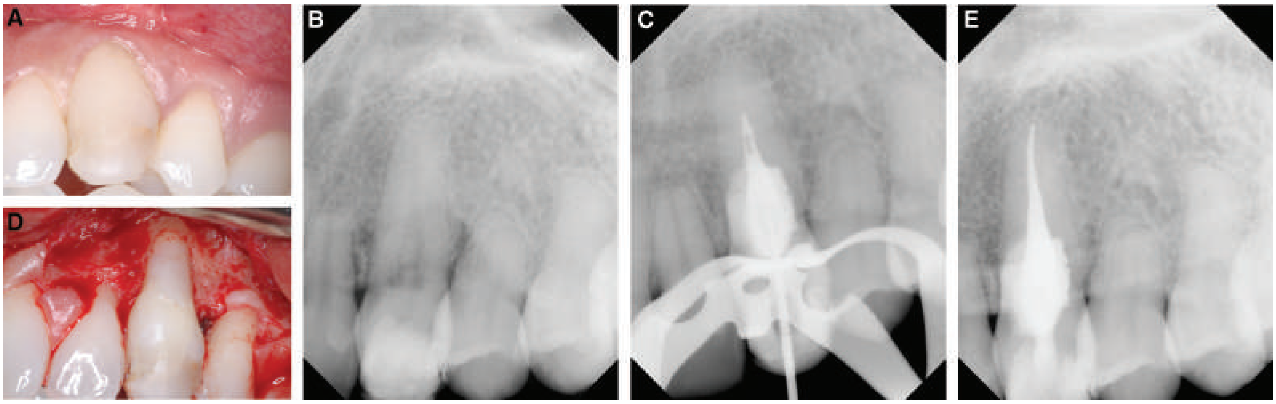

Fig. 14. Clinical procedures involved in managing a resorptive perforating defect. (A) Preoperative photograph. (B) Preoperative radiograph. (C) Radiograph showing temporary occlusion of root canal system during repair of the buccal resorptive defect. (D) Completed restoration before repositioning of soft-tissue flap. (E) Postoperative radiograph of completed case.

control hemostasis during surgery. The action of these materials, their ability to control bleeding and their effects on healing vary considerably. They aid in coagulation either through a physical tamponade action, enhancement of the clotting mechanism, vasoconstriction or a combination of each of these effects. No one local hemostatic agent is ideal; each of the available materials has advantages and disadvantages. Local hemostatic agents include collagen-based materials, ferric sulfate, calcium sulfate, epinephrine-soaked cotton or cotton pellets or cautery/electrosurgery (181). Unlike many periradicular surgical procedures, surgery in the cervical region of the tooth can sometimes be isolated using a rubber dam. The use of a rubber dam, if physically possible, provides ideal control of bleeding (Fig. 13).

Frequently, in cervical resorptive defects, the lesion will be in the region of the junction of the coronal and middle third. A small amount of bone can be chiselled away to reveal a collar of sound tooth structure (~ 1 mm). This collar of tooth structure can be used as support for an anterior rubber dam clamp. This form of 'hemostatic control' is ideal in cases where bonded restorative material is used to restore the defect.

Root surface preparation

The presence of healthy cementum on the root surface is necessary for the successful regeneration of periodontal tissues (135). A number of substances found in cementum stimulate the migration, growth and attachment of periodontal fibroblasts. Cementum extracts also activate fibroblast protein and collagen synthesis, which is necessary to re-establish a functional periodontal ligament (231–233).

Root surface conditioning is designed to remove the smear layer, thereby providing a surface that is conducive to cellular adhesion and growth. It exposes the collagenous matrix of dentine and retains biologically active substances, such as growth factors, contained in the dentine. In experimental studies, demineralized dentine induced the development of cementum-like mineralized tissue (234–238). It is argued that this treatment produces a biocompatible surface, conducive to periodontal cell colonization without compromising the adjoining periodontium. A number of solutions have been advocated for root surface modification: citric acid, tetracycline and ethylenediamine tetra-acetic acid (EDTA) (239–248). All three solutions have been shown to enhance fibroblast attachment to the root surface *in vitro* (249, 250).

Traditionally, citric acid has been the solution of choice. A 2–3 min application of an aqueous solution of citric acid (pH 1) has been recommended to etch diseased root surfaces in order to facilitate formation of new attachment and cementogenesis (251–254). Craig & Harrison (184) examined the effect on periradicular healing of citric acid demineralization of resected root ends of dogs. Use of a 1–2 min application of 50% citric acid at a pH 1 resulted in demineralized root ends, with earlier complete healing than the non-demineralized root ends. However, the beneficial effect of etching dentine surfaces with low pH solution has been questioned. Low pH may jeopardize the adjacent vital periodontal tissues. Extended applications (3 min) have been shown to discourage alveolar bone growth (242, 255–261).

EDTA, a solution with a neutral pH is equally effective in exposing collagen fibers on dentine surfaces. The benefit of EDTA over the lower pH solution is that it is not injurious to the surrounding tissues (260). An application of 15–24% EDTA for approximately 2 min produces the optimum root surface conditioning. At this concentration and time of application, EDTA at neutral pH selectively removes mineral from a dentine surface and exposes the collagen matrix. Lower pH solutions not only removed the inorganic structure but also denature the collagen matrix (242, 256, 257).

Tetracycline has also been promoted for root surface conditioning. A 30 s application removes the smear layer leaving clean and open tubules (244). There is a trend for greater connective tissue attachment following tetracycline treatment of periodontally diseased human roots. Studies comparing the effect of a 3-min application of either EDTA (pH 7.3) or tetracycline HCl (pH 1.8) showed no significant difference in the treated tooth surfaces (246). However, the application of EDTA enhanced periodontal ligament cell attachment (243).

Although the root surface conditioning effects of citric acid, EDTA and tetracycline are well documented in the periodontal literature, this treatment modality has not translated into significant gains in periodontal attachment when treating periodontally diseased teeth (248). The use of conditioning agents is not recommended when using MTA either as a perforation repair material or as a root-end filling material (262).

Guided tissue regeneration and repair of root perforations

Surgical procedures to repair perforation defects involve loose or compromised cortical bone, the result of either the disease process or the surgical procedure itself (263). This damaged cortical bone may result in reduced success for the corrective surgical procedure. Furthermore, the presence of an apico-marginal defect (264, 265) or dehiscence that is distinguished by a total loss of alveolar bone over the entire root length decreases the success of periradicular surgery significantly (266, 267). The cause of failure in these scenarios has been identified as an in-growth of non-osteogenic tissues into the surgical site and down-growth of epithelial tissue along the root surface. In these cases, successful treatment outcomes may depend more on control of the epithelial proliferation than management of defect. Guided tissue regeneration techniques have been advocated for use in such cases (6, 132, 142, 147, 263, 264, 268–284).

The basic principle of guided tissue and bone regeneration is based on the fact that different types of cells repopulate a wound at different rates during healing. The soft-tissue cells are considerably more motile than the hard-tissue cells. Therefore, they tend to migrate into the wound more rapidly during healing. A barrier interposed between the gingival tissue and the exposed root surfaces and supporting alveolar bone prevents colonization of the exposed root surface by gingival cells. This encourages the selective repopulation of the root surface by periodontal ligament cells. The use of a semi-permeable barrier theoretically would allow periodontal ligament cells and other cells with osteogenic potential to repopulate the defect, resulting in new connective tissue attachment and bone formation (271, 281, 285–290). Several case reports have also discussed the use of guided tissue regeneration techniques in conjunction with surgical perforation repair (6, 132, 142, 147, 149, 263, 272–274, 278, 291, 292).

Barriers can be grouped into two broad categories: non-resorbable and resorbable membranes. Resorbable membranes are generally better suited for endodontic applications, as a second surgical procedure is not required to remove the membrane. Frequently, membranes will require support so that the membrane does not collapse into the defect itself. In these cases, use of either a titanium-tented membrane or a supporting graft material may provide the necessary support for the membrane. Graft materials have two main functions: first as a mechanical substructure to support a membrane and the overlying soft tissues and second as a biological component that enhances bone formation.

The use of guided tissue techniques raises several additional issues that should be discussed with the patient prior to surgery. These include the cost of the additional material, the origin of the material (synthetic, animal or human), the need to manage the wound for a longer period of time and potential postoperative complications related specifically to these techniques and materials.

If guided tissue regeneration techniques are to be used in surgical perforation repair, it is advisable to use a resorbable membrane. The membrane must be extended 2.0–3.0 mm beyond the margins of the bony opening. The wound must be sutured to ensure that the tissue covers the membrane in its entirety. Compression of the tissues postoperatively is not recommended as this will collapse the membrane into the underlying defect. Furthermore, postoperative administration of antibiotics has not been shown to enhance the prognosis for these cases; however, many clinicians empirically recommend antibiotic use (129). Finally, it is not advisable to use guided tissues techniques in smokers as smoking has consistently been shown to affect the outcome adversely (293–298).

In addition to conditioning solutions and regenerative membrane techniques, the use of enamel proteins to enhance new attachment has been advocated (299–305). Emdogain is a derivative of porcine enamel proteins.

Materials available for repair of perforation defects

Historically, a plethora of materials have been suggested for use in perforation repairs (5, 27, 29, 30, 53, 63, 136, 144, 306–308). The list is expansive and the number of materials too numerous to list. Many of these materials were obviously unsuitable for use in perforation repair, while others such as amalgam (137, 309), Cavit (137, 309), indium foil, zinc-oxide cements, ethoxybenzoic acid (Super EBA) (139), composites and glass ionomers (134, 148, 309, 310) have been used quite successfully for many years. However, many of these repair procedures have resulted in the development of periodontal defects, thereby compromising the prognosis for long-term tooth retention.

The choice of material will be determined in part by the site of the perforation. Supracrestal perforations demand the use of a material such as amalgam or composite that will be resistant to dissolution by oral fluids or abrasion and erosion by foods, dentifrices or oral hygiene aids. Materials such as Intermediate Restorative Material (IRM), Super EBA, Diaket or MTA are not considered suitable materials in these situations. However, a recent report (10) demonstrates a 15-month follow-up on a case where a supracrestal perforation was repaired with MTA.

A number of materials have been developed specifically for repair of tooth structure in the subgingival area following root caries, perforations or cervical erosions. These include resin-ionomer suspensions such as Geristore and compomers such as Dyract. This group of materials attempts to combine the various properties of composite resins and glass ionomers. Both Geristore and Dyract have been recommended for use in restoring subgingival surface defects such as root surface caries, external root resorption lesions, iatrogenic root perforations and subgingival oblique fractured roots. Geristore has been shown to be an acceptable material for repair of root caries and cervical erosions in a number of clinical studies (21, 311–316). When used to repair root perforations and as an adjunct to guided tissue regeneration, results have been favorable in isolated case reports (25, 113, 317–319). When used as root-end filling materials *in vitro*, leakage assessments of Geristore and Dyract indicate that they leak less than IRM, amalgam or Super EBA (320, 321). Compared with MTA root-end fillings, Geristore has a similar leakage pattern (322). Geristore and Dyract are less sensitive to moisture than conventional glass-ionomer cement; however, dry environments produced stronger bonds (323) Geristore appears to facilitate regeneration of the periradicular tissues (324). Studies investigating epithelial and connective tissue adherence to the material show evidence of cellular attachment to the material when placed in subgingival cavities (312, 315, 316).

Repair of perforations in the subcrestal region has been greatly facilitated recently in recent years by the development of a number of new materials (105, 144, 307, 325–327) and some innovative techniques (29, 54, 64, 328). True regeneration of the periodontal architecture is possible.

Regeneration of the periradicular tissues subsequent to surgery or owing to the ravages of disease processes implies replacement of the various components of the tissue in their appropriate locations, amounts and relationships to each other (329). Repair, on the other hand, has been defined as a biological process by which continuity of disrupted tissue is restored by new tissues, which do not replicate the structure and function of the lost ones (330, 331).

Without doubt, the material that has had the greatest impact on the management of these cases is MTA. MTA was introduced to the market in the mid-1990s by Torabinejad & colleagues (10, 14, 28, 30, 144, 145, 153, 154, 306, 325, 326, 332–352). It has subsequently received FDA approval for use in pulp capping, root-end filling and perforation repair procedures (30, 144, 306). Other contemporary repair materials include Diaket, a polyvinyl resin (307, 353, 354), composite resins (148, 355), glass-ionomer materials (274, 310, 356) and compomers (113, 134, 136, 308, 312, 315, 316). When combined with tissue regenerative procedures (132, 142, 278, 281), the prognosis for many perforated teeth has been greatly improved. Both MTA and Diaket have been shown to facilitate regeneration of the periodontal apparatus following wounding (307) and have been described as osteoconductive in nature. Regeneration of the periodontal apparatus can occur when these materials are used as a root-end filling or perforation repair.

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