Rosen et al. Evidence-Based Endodontics (2018) 3:2
https://doi.org/10.1186/s41121-018-0016-7

Evidence-Based Endodontics

REVIEW Open Access

The preservation of teeth with root-originated fractures

Eyal Rosen[1*], Ilan Beitlitum[2] and Igor Tsesis[1]

Abstract

Traditionally, when a root-originated fracture (ROF) was diagnosed in an endodontically treated tooth, the tooth was scheduled for extraction. However, modern endodontics offers new treatment options to manage and maintain certain ROF teeth. The decision of whether to extract a ROF tooth and substitute it with a dental implant, or to implement a more conservative management approach by attempting an additional endodontic treatment aimed to preserve the natural tooth, is complicated and multifactorial. The management alternatives of ROF teeth range from a traditional root amputation in multi-rooted teeth to modern endodontic surgical modalities that may enable the preservation of a fractured tooth. This required decision-making process includes prosthetic, periodontal, esthetic, endodontic, and patient value concerns.

Keywords: Root-originated fracture, Vertical root fracture, Treatment, Decision-making

Introduction

Root-originated fractures (ROFs), traditionally termed "vertical root fractures," were defined as "a complete or incomplete fracture initiated from the root at any level, usually directed buccolingually" (Rivera and Walton 2008), largely based on its anatomical appearances (Tsesis et al. 2015).

Since almost all ROFs have a history of root canal treatments (RCTs) (Tsesis et al. 2015; Cuoghi et al. 2010; Tsesis et al. 2010a; Garcia-Guerrero et al. 2017; Rosen et al. 2016), it seems clear that there must be an association between RCTs and the occurrence of ROFs (Cuoghi et al. 2010; Tsesis et al. 2010a). Thus, based on the nature of these fractures, a new extended definition was recently suggested as following: "a complication of root canal treatment, characterized by a complete or incomplete fracture initiated from the root at any level, usually directed buccolingually" (Tsesis et al. 2015).

It is fundamental to understand that this extended definition of ROFs as a complication of RCTs does not imply that ROFs necessarily occur as a direct result of a practitioner's procedural error (Hofer et al. 2000). While a procedural error can lead to complications, not every complication is associated with a procedural error, and some complications may occur even when all procedures were performed adequately (Tsesis et al. 2015; Hofer et al. 2000; Angelos 2009). Since ROFs appear in teeth with either poor or good quality RCTs, ROFs must be considered as a potential complication, not necessarily a direct result of a practitioner procedural error (Tsesis et al. 2015). Therefore, this extended definition better elucidates both clinical and medico-legal aspects of ROFs (Tsesis et al. 2015; Tsesis et al. 2010a; Rosen et al. 2012).

ROFs are fairly common (Yoshino et al. 2015), with a reported prevalence of 11% up to more than 30% of extracted endodontically treated teeth (Tsesis et al. 2010a; Rosen et al. 2012). In a recent study, Yoshino et al. 2015 evaluated the prevalence of ROFs as the main reason for the extraction of the permanent teeth. They evaluated a total of 736 teeth from 24 different clinics that were extracted from 626 patients during a 6-month period. Of these teeth, a total of 233 teeth were extracted as a result of ROFs (31.7%).

Anatomically, ROFs frequently develop laterally from the root canal wall to the outer root surface (Taschieri et al. 2010). An incomplete fracture extends only on one side of the root surface, while a complete fracture develops in both directions of the root canal

* Correspondence: dr.eyalrosen@gmail.com
[1]Department of Endodontology, The Maurice and Gabriela Goldschleger School of Dental Medicine, Tel Aviv University, Tel Aviv, Israel
Full list of author information is available at the end of the article

and includes two root surfaces (Taschieri et al. 2010; Walton et al. 1984; Tamse 2006), occasionally leading to splitting of the root to segments (Tsesis et al. 2015; Taschieri et al. 2010).

A timely mannered diagnosis and proper management are critical in preventing alveolar bone loss, which may impair the future reconstructive procedures, should implant therapy be the treatment of choice (Tsesis et al. 2015; Tsesis et al. 2010a; Taschieri et al. 2010; Tamse 2006; PradeepKumar et al. 2016). However, the clinical and radiographic diagnosis of ROFs is complicated and challenging for the practitioner (Tsesis et al. 2010a; Corbella et al. 2014) and, in certain cases, is only possible by a direct observation of the suspected site following flap elevation during surgical endodontic treatment (Tsesis et al. 2015; Walton 2017) (Fig. 1).

Traditionally, teeth with ROFs were considered to have a hopeless prognosis (Tsesis et al. 2010a; Taschieri et al. 2010; Floratos and Kratchman 2012). Efforts to treat ROFs in different ways, such as by a replantation procedure with bonding of the fractured segments, have been reported (Tsesis et al. 2010a; Taschieri et al. 2010; Floratos and Kratchman 2012; Arikan et al. 2008; Kawai and Masaka 2002; Hayashi et al. 2004). However, most of these treatment attempts were found to be unpredictable and are not recommended as routine treatment alternatives (Tsesis et al. 2010a; Taschieri et al. 2010; Floratos and Kratchman 2012). Consequently, extraction was normally indicated (Tsesis et al. 2015; Taschieri et al. 2010; Tamse 2006).

Fig. 1 Diagnosis of ROF in an upper anterior tooth by a direct observation of the suspected site following flap elevation during a surgical endodontic treatment

The decision whether to attempt retaining a compromised endodontically treated tooth by additional treatments or to extract the fractured tooth and substitute it with an implant-supported restoration has been debated extensively for many years (Abboud et al. 2013; Avila et al. 2009; Bashutski and Wang 2007; Iqbal and Kim 2007; Iqbal and Kim 2008; Nemcovsky and Rosen 2017). However, in recent years, it has become evident that implants may be more prone to complications and require more postoperative maintenance than the natural tooth, and it seems that the pendulum may swing back towards endodontics and tooth preservation (Nemcovsky and Rosen 2017).

In the context of ROF teeth, in recent years, new reports suggested promising treatment alternatives aimed to preserve ROF teeth (Tsesis et al. 2010a; Taschieri et al. 2010; Floratos and Kratchman 2012; Taschieri et al. 2016) which were traditionally condemned to extraction (Tsesis et al. 2015; Tsesis et al. 2010a; Taschieri et al. 2010; Floratos and Kratchman 2012; Tsesis et al. 2006; Fabbro et al. 2009; Plotino et al. 2007). These unique treatment attempts are in their preliminary stages of development and are based mostly on case reports (Tsesis et al. 2010a; Taschieri et al. 2010; Floratos and Kratchman 2012). Still, it seems that modern endodontics offers technical means such as magnification and illumination devices (Tsesis et al. 2015; Fabbro et al. 2009; Kim and Baek 2004), and the use of modern materials such as bioceramic cements (Torabinejad and Chivian 1999) for the repair of ROFs (Tsesis et al. 2010a; Taschieri et al. 2010; Floratos and Kratchman 2012), that with proper case selection, may allow the treatment and preservation of some ROF teeth (Tsesis et al. 2015; Taschieri et al. 2016).

This manuscript will review the modern treatment options for the preservation of ROF roots.

Review

The importance of case selection

Modern endodontics provides a variety of treatment options that allow the preservation of compromised teeth (Tsesis et al. 2010b). Yet, ROFs still pose a complicated diagnostic and treatment challenge for practitioners and are a common trigger of tooth loss (Tsesis et al. 2010a; Kishen 2006). With the development of modern endodontic treatment options, new dilemmas emerged (Tsesis et al. 2015; Tsesis et al. 2010b).

A common dilemma is the decision whether to preserve a compromised tooth with ROF or to extract the fractured tooth or root and substitute it with a dental implant (Tsesis et al. 2010a; Tsesis et al. 2010b). Traditionally, it

was believed that a fast decision to extract the tooth or root may be essential because the ensuing inflammation in the surrounding periodontal tissues would lead to periodontal breakdown followed by the development of significant osseous destruction (Tsesis et al. 2010a; Walton et al. 1984; Tsesis et al. 2010b). As a result, a future restoration with dental implants in the area may be compromised (Tsesis et al. 2015; Tsesis et al. 2010a; Tamse 2006; Tsesis et al. 2010b). However, each case should be judged objectively as some data (Eichelsbacher et al. 2009) revealed that with adequate case selection, proper management of teeth affected by root-originated fractures has no detrimental impact on periodontal health over a time.

Treatment choice regarding the retention of a ROF tooth should be based on evidence-based decision-making protocol. Research evidence regarding possible treatment of a fractured tooth should be assessed, and then, taking into consideration the clinical expertise, the final treatment decision should be made in respect of patient values. Dentists should respect the patients' views about esthetic outcome, longevity, and cost associated with treatment options (Azarpazhooh et al. 2016).

When a ROF is diagnosed, the decision-making and the case selection process require a combination of endodontic, as well as periodontal, prosthetic, and esthetic considerations (Tsesis et al. 2010a; Tsesis et al. 2010b). Many factors such as the tooth location, presence of predisposing periodontal disease (Eichelsbacher et al. 2009), the kind of the coronal restoration (Tsesis et al. 2015; Iqbal and Kim 2007; Iqbal and Kim 2008; Torabinejad and Goodacre 2006; Torabinejad et al. 2008; White et al. 2006; Grossmann and Sadan 2005), the means offered by modern endodontic treatment, the options in case of treatment failure, posttreatment quality of life, and patient's values should all be evaluated and incorporated in the practitioner's decision-making. The incorporation of these concerns is vital in order to achieve a rational and evidence-based treatment plan (Tsesis et al. 2015; Tsesis et al. 2010a; Iqbal and Kim 2008; Tsesis et al. 2010b).

In multi-rooted teeth with a ROF in one of the roots, there may be no reason to attempt to treat and preserve the fractured root since there may be possible options to amputate only the fractured root (Livada et al. 2014). However, the survival of single-rooted teeth depends primarily on the ability to preserve the fractured root (Tsesis et al. 2015; Taschieri et al. 2010).

Predisposing periodontal disease in a ROF tooth may adversely affect the ability to predictably maintain the tooth (Eichelsbacher et al. 2009). Thus, a thorough clinical evaluation to determine the presence and severity of periodontal disease is therefore prudent (Avila et al. 2009).

Failure to preserve the fractured natural tooth may compromise the esthetics (Chang et al. 1999). Although in modern dentistry, osseointegration of implants is readily achievable with high long-term survival rates (Abboud et al. 2013; Bashutski and Wang 2007; Butler and Kinzer 2012; Wheeler 2007), dental implant success should be judged also by esthetic outcomes, and esthetic predictability may be difficult to attain. Furthermore, when implant failure happens in the esthetic zone, it may be difficult to be corrected entirely (Tsesis et al. 2015; Abboud et al. 2013; Bashutski and Wang 2007; Butler and Kinzer 2012; Wheelers 2007).

Nevertheless, periodontal esthetic complications, such as the development of gingival recession and alveolar bone loss, may happen as a result of the surgical procedures during the attempts to maintain the ROF tooth (Verardi 2012), especially in patients presenting with a thin periodontal biotype (Chang et al. 1999). Thus, a thorough evaluation of the esthetic-periodontal considerations should be a vital part of the treatment planning (Tsesis et al. 2015; Abboud et al. 2013; Avila et al. 2009; Bashutski and Wang 2007; Butler and Kinzer 2012; Wheeler 2007; Verardi 2012).

Many prosthetic parameters may affect the long-term prognosis of the endodontically treated teeth, such as the crown-to-root ratio, the amount of healthy tooth structure, and ferrule effect (Grossmann and Sadan 2005; Yan et al. 2017). Furthermore, an adequate coronal restoration is prudent for the long-term survival of the tooth (Tsesis et al. 2015; Lazarski et al. 2001).

In addition, due to lack of pathognomonic radiographic features or clinical signs, the ROF may be diagnosed only after the final restoration of the tooth has been completed. Thus, the type of prosthetic restoration should be considered during the decision whether to attempt additional treatments to maintain the fractured tooth (Tsesis et al. 2015; Avila et al. 2009; Sim et al. 2016). Consequently, the decision to attempt to preserve a ROF tooth by additional endodontic treatments should rely not only on the technical feasibility to treat the fracture but also on a wider spectrum of periodontal, prosthetic, and esthetic considerations that affect the risk of complications and the long-term prognosis of the tooth (Tsesis et al. 2015; Sim et al. 2016).

Treatment alternatives

When maintaining the ROF tooth is crucial for the benefit of the patient, several treatment alternatives can be considered, including root amputation or hemisection, apicoectomy that includes sectioning of the fractured root coronally to the fracture line, a replantation procedure, or flap elevation and sealing of the fracture line (Tsesis et al. 2015; Sugaya et al. 2016).

During the past few decades, various attempts to treat ROF teeth have been investigated. Although many of these attempts eventually end up in tooth extraction,

several advances have been reported in the past few years that potentially enabling predictable treatment of certain ROF teeth (Tsesis et al. 2015; Cuoghi et al. 2010; Floratos and Kratchman 2012; Arikan et al. 2008; Sim et al. 2016; Barkhordar 1991; Funato et al. 1999; Hadrossek and Dammaschke 2014; Nogueira Leal da Silva et al. 2012; Ozturk and Unal 2008; Sugaya et al. 2017).

Root amputation or hemisection

When a ROF is diagnosed in one of the roots of a posterior multi-rooted tooth, the most obvious alternative is to surgically amputate the fractured root only (Anitha and Rao 2015). About a century ago, Farrar 1884 suggested a surgical technique that included root resection and filling of the remaining part with a filling material. Farrar suggested resection of the root at different levels, sometimes leaving a short root stamp in the gingiva (Tsesis et al. 2015; Farrar 1884) (Fig. 2).

Anitha and Rao 2015 recently reported that a root resection procedure to remove the fractured root fragment entirely may predictably retain a portion of the tooth. They stated that the key to achieve predictable results depends on a careful case selection such as assuring that the remaining root has a healthy supporting periodontium, making it suitable for retention as well as restoration and support of the final prosthesis (Anitha and Rao 2015).

Depending on the specific clinical characteristics, this alternative has several subtypes such as resection of a portion of the crown along with the fractured root or, in other cases, a tooth can be extruded orthodontically to facilitate the management of the residual tooth portion (Tsesis et al. 2015; Cuoghi et al. 2010).

Root amputation or hemisection may be suggested for maxillary molars (Gupta and Kabra 2016) or mandibular molars (Anitha and Rao 2015) when just one of their roots is fractured. Depending on the periodontal condition and the level of the fracture line, the resection may be done at several levels of the root, and the coronal part of the root can sometimes be retained following a root-end treatment and filling. However, in case of fused roots, the amputation procedure is usually not recommended (Tsesis et al. 2015). It should also be noted that in the ROF mandibular molars, although a root amputation may occasionally be performed, hemisection and extraction of the fractured root or root resection is a more predictable alternative. In addition, long root trunk and short divergence of the roots have a negative influence on the surgical outcome of mandibular root resection since it is technically more difficult to perform and usually there is a need to combine it with a crown lengthening procedure (Tsesis et al. 2015).

Cementation of the root fracture following extraction and replantation

Attempts to repair the fracture following extraction of the fractured tooth and replantation of the tooth in order to preserve ROF teeth have been reported mainly in case reports and small case series (Tsesis et al. 2015; Arikan et al. 2008; Kawai and Masaka 2002; Hayashi et al. 2004; Sugaya et al. 2016; Dua and Dua 2015; Nizam et al. 2016):

Hayashi et al. 2004 described the treatment of ROFs using a replantation procedure that included repair with dentin-bonded resin. They found that 18 of 26 cases were retained and remained functional after 4 to 76 months. They also reported that the treatment of teeth with fractures spreading more than two thirds the length from the cervical portion towards the apex, as well as posterior teeth, was significantly less successful (Hayashi et al. 2004).

Nizam et al. 2016 evaluated the outcomes of 21 intentionally replanted maxillary single-rooted teeth with ROFs after being repaired extraorally using a resin cement and splinting to the adjacent teeth. They reported

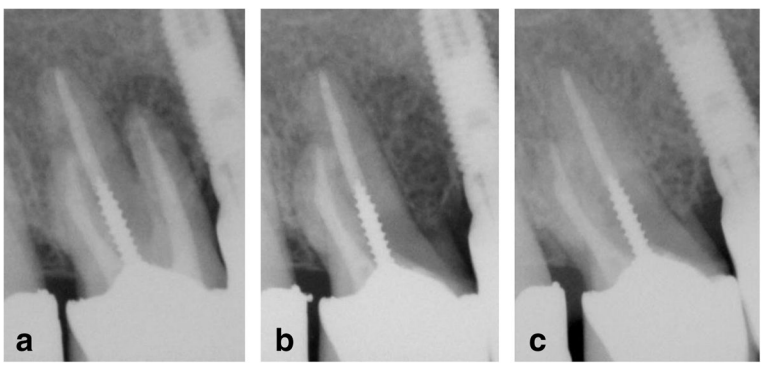

Fig. 2 Root amputation during endodontic surgery. **a** A patient presented with a sinus tract adjacent to an upper root canal treated molar. The tooth was diagnosed with chronic apical abscess, and the patient was scheduled for endodontic surgery. **b** During the surgery, a ROF was diagnosed in the mesio-buccal root and the root was amputated. **c** Two years following the surgery, the tooth was asymptomatic and was diagnosed with normal apical tissues

that two of the treated teeth were extracted in the first month following the surgery. In addition, the periodontal scores (plaque index, gingival index, probing depth, and clinical attachment level) and the periapical score index (PAI) of the treated teeth were significantly lower 12 months postoperatively when compared to baseline. They concluded that adhesive cementation and intentional replantation may be an effective treatment modality for certain ROF maxillary single-rooted teeth (Nizam et al. 2016).

Kawai and Masaka 2002 reported on an attempt to modify this treatment approach by replanting resin-bonded ROF teeth at 180 degrees rotation into the original alveolar socket in order to reposition the fracture line below the healthy bony coverage and periodontal ligaments. Others (Hadrossek and Dammaschke 2014) attempted to fill the fracture line and the retrograde preparation with a calcium-silicate-cement (Biodentine).

Although intentional replantation is generally considered a predictable treatment for certain cases (Cho et al. 2016), it should be noted that a fracture repair as part of this procedure still has an unpredictable prognosis. The foremost difficulty of this treatment modality is related to the tooth extraction that may be associated with severe complications, such as failure to extract the whole tooth in one full piece and occasional root resorption following the treatment. Therefore, the contraindications for attempting to treat ROFs by replantation include teeth which cannot be safely extracted and replanted due to an unfavorable root anatomy, a severe periodontal disease, or patients with serious general medical illnesses (Tsesis et al. 2015; Hadrossek and Dammaschke 2014).

Cementation of the root fracture following flap elevation

Attempts to achieve a direct approach to the fracture by a flap procedure and to enable its management have been reported. More than two decades ago, Selden (1996) described the treatment of teeth with incomplete ROFs using silver-glass ionomer cement and a bone graft. However, eventually, all six cases failed (Tsesis et al. 2015; Selden 1996).

Modern endodontics presents a new opportunity to efficiently treat some ROF teeth by using designated magnification and illumination devices that allow a better visualization and manipulation of the surgical field (Taschieri et al. 2016) and improving the accuracy of the surgery (Tsesis et al. 2015). Modern endodontic materials such as mineral trioxide aggregate (MTA) were proposed as sealing materials to repair ROFs (Torabinejad and Chivian 1999). The protocol includes preparation of a groove along the fracture line and sealing of the groove using MTA (Tsesis et al. 2015).

Taschieri et al. 2010 prospectively evaluated the anterior maxillary teeth diagnosed with incomplete ROFs that were treated by a modern surgical endodontic technique. Teeth with deep probing depths or with distinct radiographic appearances, such as a halo-like periradicular radiolucency, were not included in the study. Following flap elevation, a groove was ultrasonically prepared along the fracture line and then sealed with MTA. The bone defect was then filled with calcium sulfate. At the 12-month follow-up, all ten cases were successful. Then after 33 months, out of the seven cases that were available for a follow-up, five cases remained successful and two lateral incisors failed (Taschieri et al. 2010).

Floratos and Kratchman 2012 attempted a comparable procedure but in the four posterior teeth. Following a flap elevation, the fracture line was treated by a beveled resection of the root, and then a root-end preparation and filling were performed by using MTA. Eventually, the osteotomy was covered with an absorbable collagen membrane, and the teeth were followed up for 8–24 months. The teeth survived, and the treatments were successful (Floratos and Kratchman 2012).

Recently, Taschieri et al. 2016 reported on a treatment of a maxillary left central incisor suspected with an incomplete ROF. Following an exploratory flap procedure, the fracture was confirmed. Then, the fractured portion and the root-end were removed, and a platelet-rich plasma membrane was placed to cover the defect. After 24 months, the tooth was asymptomatic and the healing was in progress. The authors concluded that such a surgical approach may be considered for a combined endodontic-periodontal lesion associated with an incomplete ROF (Taschieri et al. 2016).

Although these case reports show promising results, it should be noted that such flap procedures may have some risks including a gingival scar or gingival recession formation in the esthetic zone, or additional loss of healthy bone structure as a result of the osteotomy. These risks may potentially damage the esthetic results and should be carefully considered, especially when these procedures are performed in the esthetic zone (Tsesis et al. 2015; Hadrossek and Dammaschke 2014).

Conclusions

The decision as to whether to extract a ROF tooth and substitute it with an implant-supported restoration or to attempt to maintain the compromised tooth by an additional endodontic treatment requires a multifactorial clinical decision-making process (Nemcovsky and Rosen 2017). Although extraction of the ROF tooth is usually still the treatment of choice, in specific cases, modern endodontics enables the clinician to treat and maintain ROF teeth. Additional large-scale clinical studies are required in order to better define the exact indications, protocols, and expected prognosis of these novel treatments (Tsesis et al. 2015).

Abbreviations
MTA: Mineral trioxide aggregate; PAI: Periapical score index; RCT: Root canal treatment; ROF: Root-originated fracture

Acknowledgements
The authors would like to thank Dr. Russell Paul for his assistance in proofreading.

Funding
No funding

Availability of data and materials
Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Authors' contributions
All authors contributed equally to the paper. All authors read and approved the final manuscript.

Authors' information
ER and IT are the editors-in-chief of *Evidence-Based Endodontics* journal.

Ethics approval and consent to participate
Ethics approval is not applicable. The patients gave their consent to use the relevant data, radiographs, and clinical photos.

Consent for publication
The patients gave their consent to publish the relevant data, radiographs, and clinical photos.

Competing interests
The author declares that they have no competing interests.

Publisher's Note

Author details
[1]Department of Endodontology, The Maurice and Gabriela Goldschleger School of Dental Medicine, Tel Aviv University, Tel Aviv, Israel. [2]Department of Periodontology and Dental Implantology, The Maurice and Gabriela Goldschleger School of Dental Medicine, Tel Aviv University, Tel Aviv, Israel.

Received: 23 January 2018 Accepted: 8 March 2018
Published online: 16 March 2018

References
Abboud M, Kobren LB, Orentlicher G. Implant complications: biomechanical and esthetic considerations—a prosthodontist's perspective. Compend Contin Educ Dent. 2013;34(Spec 7):20–4.
Angelos P. Complications, errors, and surgical ethics. World J Surg. 2009;33(4):609–11. https://doi.org/10.1007/s00268-008-9914-0.
Anitha S, Rao DS. Hemisection: a treatment option for an endodontically treated molar with vertical root fracture. J Contemp Dent Pract. 2015;16(2):163–5.
Arikan F, Franko M, Gurkan A. Replantation of a vertically fractured maxillary central incisor after repair with adhesive resin. Int Endod J. 2008;41(2):173–9. https://doi.org/10.1111/j.1365-2591.2007.01334.x.
Avila G, Galindo-Moreno P, Soehren S, Misch CE, Morelli T, Wang HL. A novel decision-making process for tooth retention or extraction. J Periodontol. 2009;80(3):476–91. https://doi.org/10.1902/jop.2009.080454.
Azarpazhooh A, Dao T, Ungar WJ, Da Costa J, Figueiredo R, Krahn M, et al. Patients' values related to treatment options for teeth with apical periodontitis. J Endod. 2016;42(3):365–70. https://doi.org/10.1016/j.joen.2015.11.022.
Barkhordar RA. Treatment of vertical root fracture: a case report. Quintessence Int. 1991;22(9):707–9.
Bashutski JD, Wang HL. Common implant esthetic complications. Implant Dent. 2007;16(4):340–8. https://doi.org/10.1097/ID.0b013e318159ca05.
Butler B, Kinzer GA. Managing esthetic implant complications. Compend Contin Educ Dent. 2012;33(7):514–8. 20-2
Chang M, Odman PA, Wennstrom JL, Andersson B. Esthetic outcome of implant-supported single-tooth replacements assessed by the patient and by prosthodontists. Int J Prosthodont. 1999;12(4):335–41.
Cho SY, Lee Y, Shin SJ, Kim E, Jung IY, Friedman S, et al. Retention and healing outcomes after intentional replantation. J Endod. 2016;42(6):909–15. https://doi.org/10.1016/j.joen.2016.03.006.
Corbella S, Del Fabbro M, Tamse A, Rosen E, Tsesis I, Taschieri S. Cone beam computed tomography for the diagnosis of vertical root fractures: a systematic review of the literature and meta-analysis. Oral Surg Oral Med Oral Pathol Oral Radiol. 2014;118(5):593–602. https://doi.org/10.1016/j.oooo.2014.07.014.
Cuoghi OA, Bosco AF, de Mendonca MR, Tondelli PM, Miranda-Zamalloa YM. Multidisciplinary treatment of a fractured root: a case report. Aust Orthod J. 2010;26(1):90–4.
Del Fabbro M, Taschieri S, Lodi G, Banfi G, Weinstein RL. Magnification devices for endodontic therapy. Cochrane Database Syst Rev. 2009;3:CD005969. https://doi.org/10.1002/14651858.CD005969.pub2.
Dua D, Dua A. Reconstruction and intentional replantation of a maxillary central incisor with a complete vertical root fracture: a rare case report with three years follow up. J Clin Diagn Res. 2015;9(9):ZD06–9. https://doi.org/10.7860/JCDR/2015/13853.6476.
Eichelsbacher F, Denner W, Klaiber B, Schlagenhauf U. Periodontal status of teeth with crown-root fractures: results two years after adhesive fragment reattachment. J Clin Periodontol. 2009;36(10):905–11. https://doi.org/10.1111/j.1600-051X.2009.01458.x.
Farrar JN. Radical and heroic treatment of alveolar abscess by amputation of roots of teeth. Dental Cosmos. 1884;26:79.
Floratos SG, Kratchman SI. Surgical management of vertical root fractures for posterior teeth: report of four cases. J Endod. 2012;38(4):550–5. https://doi.org/10.1016/j.joen.2011.12.030.
Funato A, Funato H, Matsumoto K. Treatment of a vertical root fracture. Endod Dent Traumatol. 1999;15(1):46–7.
Garcia-Guerrero C, Parra-Junco C, Quijano-Guauque S, Molano N, Pineda GA, Marin-Zuluaga DJ. Vertical root fractures in endodontically-treated teeth: a retrospective analysis of possible risk factors. J Investig Clin Dent. 2017; https://doi.org/10.1111/jicd.12273.
Grossmann Y, Sadan A. The prosthodontic concept of crown-to-root ratio: a review of the literature. J Prosthet Dent. 2005;93(6):559–62.
Gupta A, Kabra P. Resective procedure in the management of maxillary molar with horizontal/oblique root fractures: a case report. Journal of Dental and Medical Sciences. 2016;15(7):66–9.
Hadrossek PH, Dammaschke T. New treatment option for an incomplete vertical root fracture—a preliminary case report. Head Face Med. 2014;10:9. https://doi.org/10.1186/1746-160X-10-9.
Hayashi M, Kinomoto Y, Takeshige F, Ebisu S. Prognosis of intentional replantation of vertically fractured roots reconstructed with dentin-bonded resin. J Endod. 2004;30(3):145–8. https://doi.org/10.1097/00004770-200403000-00005.
Hofer TP, Kerr EA, RA H. What is an error? Eff Clin Pract. 2000;3(6):261–9.
Iqbal MK, Kim S. For teeth requiring endodontic treatment, what are the differences in outcomes of restored endodontically treated teeth compared to implant-supported restorations? Int J Oral Maxillofac Implants. 2007;22(Suppl):96–116.
Iqbal MK, Kim S. A review of factors influencing treatment planning decisions of single-tooth implants versus preserving natural teeth with nonsurgical endodontic therapy. J Endod. 2008;34(5):519–29.
Kawai K, Masaka N. Vertical root fracture treated by bonding fragments and rotational replantation. Dent Traumatol. 2002;18(1):42–5.
Kim S, Baek S. The microscope and endodontics. Dent Clin N Am. 2004;48(1):11–8. https://doi.org/10.1016/j.cden.2003.12.001.
Kishen A. Mechanisms and risk factors for fracture predilection in endodontically treated teeth. Endod Top. 2006;13(1):57–83.
Lazarski MP, Walker WA 3rd, Flores CM, Schindler WG, Hargreaves KM. Epidemiological evaluation of the outcomes of nonsurgical root canal treatment in a large cohort of insured dental patients. J Endod. 2001;27(12):791–6.
Livada R, Fine N, Shiloah J. Root amputation: a new look into an old procedure. N Y State Dent J. 2014;80(4):24–8.
Nemcovsky CE, Rosen E. Biological complications in implant-supported oral rehabilitation: as the pendulum swings back towards endodontics and tooth preservation. Evidence-Based Endodontics. 2017;2(4):1–8. https://doi.org/10.1186/s41121-017-0010-5.
Nizam N, Kaval ME, Gurlek O, Atila A, Caliskan MK. Intentional replantation of adhesively reattached vertically fractured maxillary single-rooted teeth. Int Endod J. 2016;49(3):227–36. https://doi.org/10.1111/iej.12444.

Nogueira Leal da Silva EJ, Romao Dos Santos G, Liess Krebs R, Coutinho-Filho Tde S. Surgical alternative for treatment of vertical root fracture: a case report. Iran Endod J. 2012;7(1):40–4.
Ozturk M, Unal GC. A successful treatment of vertical root fracture: a case report and 4-year follow-up. Dent Traumatol. 2008;24(5):e56–60. https://doi.org/10.1111/j.1600-9657.2008.00705.x.
Plotino G, Pameijer CH, Grande NM, Somma F. Ultrasonics in endodontics: a review of the literature. J Endod. 2007;33(2):81–95. https://doi.org/10.1016/j.joen.2006.10.008.
PradeepKumar AR, Shemesh H, Jothilatha S, Vijayabharathi R, Jayalakshmi S, Kishen A. Diagnosis of vertical root fractures in restored endodontically treated teeth: a time-dependent retrospective cohort study. J Endod. 2016;42(8):1175–80. https://doi.org/10.1016/j.joen.2016.04.012.
Rivera E, Walton ER. Cracking the cracked tooth code: detection and treatment of various longitudinal tooth fractures. Colleagues for excellence, Summer 2008. Chicago: American association of endodontics; 2008.
Rosen E, Beitlitum I, Tamse A, Taschieri S, Tsesis I. Implant-associated vertical root fracture in adjacent endodontically treated teeth: a case series and systematic review. J Endod. 2016;42(6):948–52. https://doi.org/10.1016/j.joen.2016.03.021.
Rosen E, Tsesis I, Tamse A, Bjorndal L, Taschieri S, Givol N. Medico-legal aspects of vertical root fractures in root filled teeth. Int Endod J. 2012;45(1):7–11. https://doi.org/10.1111/j.1365-2591.2011.01938.x.
Selden HS. Repair of incomplete vertical root fractures in endodontically treated teeth—in vivo trials. J Endod. 1996;22(8):426–9. https://doi.org/10.1016/S0099-2399(96)80245-7.
Sim IG, Lim TS, Krishnaswamy G, Chen NN. Decision making for retention of endodontically treated posterior cracked teeth: a 5-year follow-up study. J Endod. 2016;42(2):225–9. https://doi.org/10.1016/j.joen.2015.11.011.
Sugaya T, Tomita M, Motoki Y, Miyaji H, Kawamami M. Influence of enamel matrix derivative on healing of root surfaces after bonding treatment and intentional replantation of vertically fractured roots. Dent Traumatol. 2016;32(5):397–401. https://doi.org/10.1111/edt.12270.
Sugaya T, Tomita M, Motoki Y, Zaman K, Miyaji H, Kawanami M. Periodontal tissue repair after sealing of the gap in vertical root fracture. Odontology. 2017;105(2):202–7. https://doi.org/10.1007/s10266-016-0270-5.
Tamse A. Vertical root fractures in endodontically treated teeth: diagnostic signs and clinical management. Endod Top. 2006;13(1):84–94.
Taschieri S, Del Fabbro M, El Kabbaney A, Tsesis I, Rosen E, Corbella S. Microsurgical re-treatment of an endodontically treated tooth with an apically located incomplete vertical root fracture: a clinical case report. Restor Dent Endod. 2016;41(4):316–21. https://doi.org/10.5395/rde.2016.41.4.316.
Taschieri S, Tamse A, Del Fabbro M, Rosano G, Tsesis I. A new surgical technique for preservation of endodontically treated teeth with coronally located vertical root fractures: a prospective case series. Oral Surg Oral Med Oral Pathol Oral Radiol Endod. 2010;110(6):e45–52. https://doi.org/10.1016/j.tripleo.2010.07.014.
Torabinejad M, Chivian N. Clinical applications of mineral trioxide aggregate. J Endod. 1999;25(3):197–205. https://doi.org/10.1016/S0099-2399(99)80142-3.
Torabinejad M, Goodacre CJ. Endodontic or dental implant therapy: the factors affecting treatment planning. J Am Dent Assoc. 2006;137(7):973–7. quiz 1027-8
Torabinejad M, Lozada J, Puterman I, White SN. Endodontic therapy or single tooth implant? A systematic review. J Calif Dent Assoc. 2008;36(6):429–37.
Tsesis I, Beitlitum I, Rosen E. Treatment alternatives for the preservation of vertically root fractured teeth. In: Rosen TT, editor. Vertical root fractures in dentistry. Switzerland: Springer International Publishing; 2015. p. 97–107.
Tsesis I, Nemkowsky CE, Tamse E, Rosen E. Preserving the natural tooth versus extraction and implant placement: making a rational clinical decision. Refuat Hapeh Vehashinayim. 2010b;27(1):37–46. 75
Tsesis I, Rosen E, Schwartz-Arad D, Fuss Z. Retrospective evaluation of surgical endodontic treatment: traditional versus modern technique. J Endod. 2006;32(5):412–6. https://doi.org/10.1016/j.joen.2005.10.051.
Tsesis I, Rosen E, Tamse A, Taschieri S, Kfir A. Diagnosis of vertical root fractures in endodontically treated teeth based on clinical and radiographic indices: a systematic review. J Endod. 2010a;36(9):1455–8. https://doi.org/10.1016/j.joen.2010.05.003.
Verardi S. Apical surgery may cause gingival recession. J Evid Based Dent Pract. 2012;12(3 Suppl):143–4. https://doi.org/10.1016/S1532-3382(12)70026-X.
Walton RE. Vertical root fracture: factors related to identification. J Am Dent Assoc. 2017;148(2):100–5. https://doi.org/10.1016/j.adaj.2016.11.014.
Walton RE, Michelich RJ, Smith GN. The histopathogenesis of vertical root fractures. J Endod. 1984;10(2):48–56. https://doi.org/10.1016/S0099-2399(84)80037-0.
Wheeler SL. Implant complications in the esthetic zone. J Oral Maxillofac Surg. 2007;65(7 Suppl 1):93–102. https://doi.org/10.1016/j.joms.2007.03.009.
White SN, Miklus VG, Potter KS, Cho J, Ngan AY. Endodontics and implants, a catalog of therapeutic contrasts. J Evid Based Dent Pract. 2006;6(1):101–9.
Yan W, Montoya C, Oilo M, Ossa A, Paranjpe A, Zhang H, et al. Reduction in fracture resistance of the root with aging. J Endod. 2017;43(9):1494–8. https://doi.org/10.1016/j.joen.2017.04.020.
Yoshino K, Ito K, Kuroda M, Sugihara N. Prevalence of vertical root fracture as the reason for tooth extraction in dental clinics. Clin Oral Investig. 2015;19(6):1405–9. https://doi.org/10.1007/s00784-014-1357-4.