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REVIEW

Present status and future directions: Endodontic management of traumatic injuries to permanent teeth

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Abstract

The prognosis of traumatized teeth depends largely on the fate of the pulp and its treatment. This review aims to update the present status on the endodontic management of traumatic injuries to permanent teeth and to identify relevant research areas that could contribute to an improvement in diagnosis and treatment of traumatized permanent teeth. Future research should pay greater attention to (1) diagnostic methods to assess the perfusion of the pulp and enhance detection of tooth cracks and initial signs of root resorption; (2) improved materials for vital pulp treatment; (3) studies focusing on type and duration of splinting after root fractures; (4) antiresorptive intracanal medication in case of posttraumatic pulp necrosis and infection-related resorption and (5) long-term data on the apical barrier technique compared to revitalization.

KEYWORDS

avulsion, dental trauma, diagnosis, endodontic management, tooth fracture, tooth injuries

INTRODUCTION

A recent bibliometric analysis has revealed that dental traumatology remains an evolving field of research with a large number of publications over the last two decades (Liu et al., 2020).

The considerable number of articles in journals which focus on endodontology underlines the important role of the pulp in the management of traumatized teeth. Despite this high research activity, there is a lack of high-quality well-designed studies in some areas.

In addition to the recently published comprehensive review and the position statement of the European Society of Endodontology (ESE, 2021; Krastl et al., 2021), this review aims to update the present status on the endodontic management of traumatic dental injuries (TDIs) in the permanent dentition and to identify relevant research areas that could contribute to an improvement in diagnosis and treatment of traumatized teeth.

THE CONDITION OF THE TRAUMATIZED PULP: PRESENT STATUS

In general, an accurate diagnosis of the condition of the pulp is of utmost importance in order to make the correct treatment decision; however, none of the available diagnostic tests can clearly distinguish a treatable from a non-treatable pulpal condition (Mejare et al., 2012). Particularly after TDIs, further limitations can complicate the diagnosis. Patient compliance is required, which might not be granted due to young patient age or distress after the traumatic impact, leading to false results. Commonly used sensibility tests are based on thermal or electric stimulation. Thermal tests activate hydrodynamic movement of fluid within dentinal tubules, which excites the A-delta fibres, whilst electric pulp tests result in a direct stimulation of the A-delta fibres (Jafarzadeh & Abbott, 2010). Both tests are physiologically dependent on a functional vascular supply. Therefore, reaction to sensibility testing is used as an indirect indicator (surrogate) of a vital pulp. These limitations of conventional pulp testing make diagnostics following trauma challenging, as temporary loss of sensibility occurs frequently due to pulpal oedema after luxation injuries. In such cases, it may take a few to several weeks before a response to sensibility testing returns (Bastos et al., 2014; Rock & Grundy, 1981; Skieller, 1960). Thus, no reaction to sensibility testing after trauma does not necessarily indicate pulp necrosis; it rather indicates damage to the pulpal tissues with consequences regarding prognosis, as an intact vascular supply is responsible for pulp survival. Additional difficulties may occur after repeated injuries, which can influence sensibility testing and the healing capacity of the pulp. Furthermore, neural regeneration progresses at a slower rate compared to vascular regeneration or may even fail to re-appear (Kvinnsland et al., 1992; Schendel et al., 1990), which again conflicts with the nature of sensibility testing.

On the other hand, vitality tests (e.g. laser Doppler flowmetry, ultrasound Doppler flowmetry, pulse oximetry) assess the blood supply of the pulp, thus offering a more objective approach. Whereas vitality tests have been reported to have superior diagnostic accuracy compared to sensibility tests (Balevi, 2019; Ghouth et al., 2018; Lima et al., 2019), there might be a high level of bias (Ghouth et al., 2019), and their complicated clinical application makes the benefits of these tests questionable (Alghaithy & Qualtrough, 2017). Another factor that has to be considered when assessing pulpal status after dental trauma is the stage of root development. Immature teeth are not fully innervated and therefore associated with an increased excitation threshold (Fulling & Andreasen, 1976), which may result in increased rates of false negative results, particularly after electric pulp testing (Fuss et al., 1986; Rock & Grundy, 1981). Colour changes may be concomitant observations in traumatized teeth and may result from pulpal haemorrhage (Andreasen, 1986). Pink colour changes that occur shortly after the accident can be reversible. However, if the crown of the tooth turns progressively grey, this may indicate pulp necrosis (Malmgren & Hubel, 2012).

All these factors have to be borne in mind when performing sensibility testing of the pulp after dental trauma, and obtaining the correct pulp diagnosis is only possible through combining and assimilating findings from the patients' history, analysis of the injury pattern, further diagnostics as well as radiographic assessment, which are all an integral part of the diagnostic process.

Despite the limitations of conventional 2D radiography in visualizing three-dimensional anatomical structures, periapical (PA) radiographs combined with clinical examination remains the standard of care and should always be considered during the initial evaluation of the patient (Bourguignon et al., 2020).

Cone beam computed tomography (CBCT) can provide valuable additional information but its use should always be balanced against the potential risks (ESE, 2019a). On the one hand, cases that appear straightforward on periapical radiographs might present a different and more complex situation when evaluated three-dimensionally (Cohenca & Silberman, 2017). At the same time, it should be taken into account, that particularly in children, the tissues are more sensitive to the effects of ionizing radiation (Whitworth, 2018) with children below the age of 10 years having a 3-fold probability of radiation-induced stochastic effects compared to those over 30 years of age (Horner et al., 2004). Thus, CBCTs should be considered in situations in which further imaging is required to obtain an accurate diagnosis and develop a correct treatment plan and where the image is likely to change the management of the injury (Bourguignon et al., 2020). This applies particularly to cases of complex dento-alveolar trauma, such as root fractures where a communication of the fracture lines with the oral cavity appears likely and to complications such as root resorptions (Dula et al., 2014; ESE, 2019a).

THE CONDITION OF THE TRAUMATIZED PULP: FUTURE DIRECTIONS

To overcome the limitations of current diagnostic procedures, further advancement of current vitality tests (laser Doppler flowmetry, ultrasound Doppler flowmetry, pulse oximetry) and development of new methods are highly desirable in order to provide a simple approach to reliably assess the perfusion of the pulp in routine clinical practice. Furthermore, magnetic resonance imaging (MRI) can be used to visualize perfusion of the pulp (Assaf et al., 2015). It remains to be answered under which conditions MRI might be a useful diagnostic tool in dental traumatology. Further, the traumatic displacement of the apex of the tooth might be used as a potential surrogate measure to pulp damage. It is conceivable that in the future, intraoral scans might be used on a regular basis during routine dental examinations (Suese, 2020). In case of luxation injuries in the permanent dentition, a post traumatic scan in combination with a CBCT can be used to accurately determine the amount of traumatic displacement of the root tip compared to the stored data of the affected arch (Lee, 2021). Clinical studies might help to correlate direction and amount of displacement with survival of the pulp, thus providing helpful treatment recommendations.

ENDODONTIC MANAGEMENT OF TRAUMATICALLY EXPOSED DENTINE: PRESENT STATUS

After TDIs, dentine may be exposed following crown fractures and crown-root fractures but even enamel cracks extending into the dentine may represent potential pathways for the invasion of microorganisms (Love, 1996). An infection of a healthy pulp via this pathway leading to necrosis is unlikely with a risk that has been reported to be less than 3.5% (Ravn, 1981a; Stalhane & Hedegard, 1975). However, the risk of pulp necrosis may increase in the presence of an undiagnosed concussion or subluxation of the affected tooth due to a compromised blood supply.

Adhesive sealing of enamel cracks has been reported to be effective in laboratory studies in order to prevent pulp infection (Love, 1996). However, there is no clinical evidence whether sealing a crack increases the fracture resistance of the crown or prevents pulp necrosis or discolouration of the crack lines.

Most crown fractures expose dentine. In children, up to 70 000 tubules per mm^2 with a diameter of 2–5 μm and communication with the pulp may be exposed (Garberoglio & Brannstrom, 1976; Ketterl, 1961). Due to an age-related smaller volume of peritubular dentine, a large percentage of the total cross-sectional area in close proximity to the pulp consists of lumina of dentinal tubules; therefore, the fractured dentine is highly permeable (Mjor, 2009). Defence mechanisms of the pulp such as the outward flow of fluid through the dentinal tubules and the ability of the pulp to react to external stimuli with an immediate inflammatory response temporarily impede bacterial invasion and infection of the pulp tissue (Olsburgh et al., 2002). Nevertheless, if major fractures are left without protection of the dentine wound, pulp necrosis is likely to occur in more than 50% of the cases (Ravn, 1981b). The risk of pulp necrosis is increased further in cases of concomitant luxation injuries due to a compromised apical blood supply (Robertson et al., 2000). Therefore, a definitive adhesive restoration (fragment reattachment or direct composite restoration) should be placed as soon as possible after the accident. If this is not feasible during the initial emergency treatment, placement of the restoration can be postponed if the dentinal wound is sealed properly to prevent pulp infection. Immediate dentine sealing can be carried out using a dentine bonding agent and a layer of flowable composite. Temporary dentine protection with calcium hydroxide cement or glass ionomer cement may be less effective but can be applied if subsequent treatment takes place within the next few days (Krastl et al., 2020). Under optimal conditions, the prognosis is favourable but periodic reevaluation is recommended to determine the pulpal status.

ENDODONTIC MANAGEMENT OF TRAUMATICALLY EXPOSED DENTINE: FUTURE DIRECTIONS

Whilst fibre-optic transillumination enables detection of enamel cracks, it does not provide information on the extension into dentine. Optical coherence tomography (OCT), a nondestructive imaging technique, first introduced more than two decades ago for imaging of dental tissues (Colston et al., 1998) can add in-depth information and could be used to assess crack progression (Imai et al., 2012; Shimada et al., 2020). Thus, OCT may be a valuable diagnostic tool for cracks resulting from dental trauma if appropriate equipment for routine clinical use becomes available.

ENDODONTIC MANAGEMENT OF THE TRAUMATICALLY EXPOSED PULP: PRESENT STATUS

Most crown fractures occur in children and young patients and usually involve teeth without preexisting pulpal damage from caries or previous dental trauma. Therefore, it can generally be assumed that the traumatically exposed pulps are healthy and capable of regeneration.

Primate models studying the tissue reaction following experimental exposure of pulps to the oral environment demonstrated the presence of inflammatory cells in the pulp at the exposure site. However, during the first hours of exposure, the tissue alterations rather reflect the damage resulting from the mechanical trauma with negligible superficial inflammatory changes (Cox et al., 1982; Heide & Mjor, 1983). After 7 days of exposure, the inflammatory response has been reported to be more pronounced but does not extend more than 2 mm into the pulpal tissue (Cvek et al., 1982). Thus, the conditions for vital pulp treatment (VPT) are favourable at least within the first days after trauma. Independent of the treatment strategy, it is essential that the tooth is isolated with rubber dam and disinfected prior to VPT (ESE, 2019b). Furthermore, the use of sterile instruments and magnification are highly recommended throughout the entire procedure.

Direct pulp capping aims to maintain the vitality of the entire pulp after application of a biomaterial directly onto the exposed tissue (ESE, 2019b). Animal studies suggest that direct pulp capping may be successful even if delayed for 24 h (Cox et al., 1982; Pitt Ford & Roberts, 1991). Nevertheless, direct pulp capping after trauma is usually recommended for small pulp exposures which are treated shortly after the injury (Cvek, 1978; Krastl & Weiger, 2014). Thus, partial pulpotomy is preferable for the majority of cases, particularly if a large area of the pulp is exposed and the treatment cannot be performed within the first few hours after the injury (Dammaschke et al., 2019a; Krastl et al., 2020).

Partial pulpotomy is preferably performed using a small cylindrical diamond bur in a high-speed handpiece under continuous irrigation and involves removing approximately 2 mm of the coronal pulp. Similarly to direct capping, rinsing the pulp wound with sodium hypochlorite (0.5%–5%) is particularly recommended during partial pulpotomy to assist haemostasis and disinfection (ESE, 2019b; Munir et al., 2020). Cotton wool or sponge pellets soaked in sodium hypochlorite can be applied with gentle pressure. If the remaining pulp is reduced to a healthy level, bleeding is expected to stop within 5 min. If haemostasis has not occurred within this time frame, the removal of the entire coronal pulp (full pulpotomy), can be considered as the last measure to maintain the vitality of the radicular pulp. The absence of any bleeding following pulp amputation is associated with a compromised blood supply to the pulp and is a negative predictor for the success of VPT.

Before starting the capping procedure, the operator must ensure that there is no blood clot on top of the exposed pulp. The selection of the capping material for direct pulp capping and partial pulpotomy primarily depends on its bioactive properties but should also take the risk of crown discolouration into account.

Calcium hydroxide is still commonly used as a pulp capping material and has been reported to have high success rates (Dammaschke et al., 2019a) despite its mechanical instability and the dissolution of the material over time (Bakland & Andreasen, 2012). Thus, calcium hydroxide is highly dependent on the protection of a high-quality restoration to prevent bacterial invasion of the pulp (Bakland, 2009). Hydraulic calcium silicate-based cements (HCSC) overcome the problem of mechanical instability, at the same time they offer excellent biological properties. The drawback of some of these materials is their discolouration potential caused by the included radiopacifiers and by absorption of blood components due to porosities within the material (Krastl et al., 2013; Lenherr et al., 2012). Newer formulations of these materials that contain zirconium oxide or tantalum oxide appear more colour-stable (Dettwiler et al., 2016; Haikal et al., 2020; Lipski et al., 2018; Mozynska et al., 2017).

A large variety of bioactive materials are available on the market, all of them sharing calcium-silicate-chemistry with desirable biological effects. However, the use of light-curing liners and cements with calcium hydroxide or MTA-additives as pulp capping agents cannot be recommended now due to the paucity of reliable data regarding biocompatibility and due to potentially toxic effects of the monomer components (Camilleri et al., 2014; Dammaschke et al., 2019a; Hebling et al., 2009). Likewise, dentine adhesives and composite resins are not biocompatible and therefore cannot be recommended as pulp capping materials (Costa et al., 2000; Dammaschke et al., 2019a).

After application of non-staining HCSC or a calcium hydroxide suspension onto the exposed pulp, the capping material must be covered with a thin layer of a hard-setting material, to avoid unintentional removal during the restorative procedures that follow. Subsequently, the exposed dentine should be rinsed thoroughly and cleaned with water to minimize the negative impact of disinfecting solutions on the adhesive bond. The definitive adhesive restoration should ideally be applied during the same visit. Partial pulpotomy can be performed during initial trauma care. It can also be carried out secondary to emergency pulp capping after a few days without compromising success (Wang et al., 2017).

A hard tissue bridge with histological evidence of tubular dentine may form over the healed pulp tissue (Nair et al., 2008). However, in most cases, bridge formation after pulp capping procedures is rather regarded a repair process due to its unstructured mineralization and lack of native tubular morphology (Dammaschke et al., 2019b).

In contrast to VPT of cariously exposed pulps where HCSCs clearly outperform calcium hydroxide in terms of clinical success (ESE, 2019b), in the treatment of traumatically exposed pulps, the capping material (calcium hydroxide vs. HCSC) does not seem to be a decisive factor (Bissinger et al., 2021; Dammaschke et al., 2019a). A retrospective study demonstrated a significantly higher success rate when a new generation of HSCS was used instead of calcium hydroxide, however the latter still achieved a clinical success rate of 93% (Rao et al., 2020). A randomized controlled trial demonstrated a similar pulp survival rate in traumatized immature teeth treated with partial pulpotomy regardless of whether calcium hydroxide or a new generation of HSCS was used as a capping material (Yang et al., 2020).

Thus, calcium hydroxide can still be used but specific non-staining HCSC are the first choice (Abuelniel et al., 2020; Haikal et al., 2020; Parinyaprom et al., 2018).

Survival of the pulp after complicated crown fractures can be achieved in 43%–90% with direct pulp capping (Fuks et al., 1982; Hecova et al., 2010; Ravn, 1982; Wang et al., 2017) and 86%–100% with partial pulpotomy (de Blanco, 1996; Cvek, 1978, 1993; Fuks et al., 1987; Hecova et al., 2010; Wang et al., 2017). Given the greater success rates of partial pulpotomy compared to direct pulp capping, the indication for direct pulp capping can be questioned.

Partial pulpotomy after trauma is associated with very high success rates particularly in immature teeth (90%–100%) but also high success rates ranging from 70% to 100% in mature teeth (de Blanco, 1996; Cvek, 1978, 1993; Fuks et al., 1987; Hecova et al., 2010; Wang et al., 2017). With increasing age of the patient, alterations in terms of a reduced cell density and an increased amount of fibrous tissue may reduce the pulp tissue's regenerative capacity (Goodis et al., 2012; Murray et al., 2002). Nevertheless, vital pulp treatment after trauma should not be reserved for children and adolescents only but should be considered for adults as well. However, particularly in teeth with completed root formation, even minor luxation injuries may compromise the nutritional supply to the pulp, and therefore substantially affect the success of vital pulp treatment (Lauridsen et al., 2012a, 2012b, 2012c; Ravn, 1981b; Robertson et al., 2000). Teeth that have undergone pulp preservation procedures should be periodically monitored to assess the treatment outcome (Jafarzadeh & Abbott, 2010).

ENDODONTIC MANAGEMENT OF THE TRAUMATICALLY EXPOSED PULP: FUTURE DIRECTIONS

Whilst the success rates achieved with VPT of traumatically exposed pulps hardly offer much room for improvement, both handling characteristics and aesthetic properties of HCSCs may be improved further. Fast-setting and highly colour-stable HCSC materials can favourably influence VPT of traumatically exposed pulps.

Even though observational and retrospective data suggest a similar distribution of success rates after partial pulpotomy irrespective of patient age, additional research is needed to provide a reliable body of evidence on vital pulp treatment in adults and elderly patients.

ENDODONTIC MANAGEMENT FOLLOWING ROOT FRACTURES: PRESENT STATUS

Intra-alveolar root fractures of permanent teeth with vital pulps result in an injury to the pulp tissues, primarily compromising the neurovascular supply coronal to the fracture line. Maxillary anterior teeth are most often affected in this way. The condition of the pulp following displacement of the coronal tooth fragment can only be estimated at the first clinical examination and continuous monitoring is necessary to make a final diagnosis of the pulpal status.

Previous traumatic events and the age of the patient have been suggested to impact pulp survival (Andreasen et al., 2004a, 2004b). The validity of any sensibility test is limited during the first weeks after the traumatic event. An initially negative response is not a clear indicator that the pulp will not recover. Pulp healing is more likely in immature teeth as well as in teeth with root fractures with a positive pulp reaction at the time of first examination following the accident (Andreasen & Kahler, 2015).

A reddish discolouration of the crown may occur immediately after the injury in some cases as a result of diffusion of blood components into dentine. This discolouration may either remain or disappear (transient coronal discolouration; Heithersay & Kahler, 2013) and is not necessarily a sign of pulp necrosis.

The various root resorption processes that may occur following root fracture are usually related to marked osteoclastic activity during the healing process and do not require endodontic treatment (Andreasen & Andreasen, 1988). External surface resorption may lead to a rounding of the fracture edges and may be associated with a widening of the fracture line during the initial phases of fracture healing (Andreasen & Hjorting-Hansen, 1967). Internal surface resorption has been described as a circular radiolucent area starting at the intersection of root canal and fracture line due to a rounding of the fracture edges at the pulpal aspect of the fracture (Andreasen & Andreasen, 1988). Internal tunnelling resorption likewise begins at the fracture line but burrows behind the predentin layer of the root canal walls. Furthermore, partial to complete obliteration is a common finding on follow-up radiographs taken after some months, affecting almost three quarters of the teeth with root fractures. In the majority of cases either the apical fragment or both the apical and coronal fragment are affected, but rarely the coronal fragment alone (Andreasen & Andreasen, 1988). In almost 80% of treated teeth with intra-alveolar fractures (below the alveolar bone crest level), favourable healing with either hard tissue fusion of the fragments (30%) or interposition of soft tissues (with or without bone formation) in-between the fragments (48%) has been demonstrated (Andreasen et al., 2004a). Surprisingly, in intra-alveolar cervical fractures, the chance of pulp healing is greater compared to fractures located at the middle or apical third of the root. This might be explained by the larger fracture foramen (the diameter of the root canal where the fracture line is crossing) in the coronal fragment and the shorter distance needed to be revascularized in the cervical region (Andreasen et al., 2004a). Nevertheless, even if healing occurs initially, the prognosis of teeth with cervical root fractures is poor because the highly mobile coronal fragment is prone to further traumatic displacement (Andreasen et al., 2012a). Orthodontic retainers may stabilize the tooth and increase its longevity (Tobiska & Krastl, 2018) but clinical evidence is missing. However, if there is an initially undiagnosed communication of the fracture line to the oral environment via the gingival sulcus, extraction of the coronal fragment is inevitable (Andreasen et al., 2012a). Preservation of the root and subsequent restorative treatment may still be possible following surgical extrusion (Kahnberg, 1996). Apart from the fracture location, the extent of dislocation of the coronal fragment (i.e. displacement in any direction) and tooth mobility are positively associated with the risk of later pulp necrosis (Andreasen et al., 2004a).

Clinical signs indicating a loss of pulp vitality appear within the first three to six months, in some cases even later. The lack of a response to pulp sensibility testing is not conclusive for pulp necrosis (Bourguignon et al., 2020). Thus, at least two symptoms, such as recurrent negative response to vitality or sensibility tests and a grey discolouration of the crown should be present for a reliable clarification of the tentative diagnosis (Jacobsen, 1980). Pulp necrosis followed by endodontic infection of the coronal fragment and inflammatory changes between fragments was detected in 22% of cases (Andreasen et al., 2004a). In these cases, a lateral lesion at the level of the fracture line is detected radiographically as a result of an infection of the coronal root canal system (Andreasen & Hjorting-Hansen, 1967). This lesion can often be diagnosed within the first year which underlines the necessity of regular follow-ups. In immature teeth, arrested root development is a typical sign of pulp deterioration. The pulp tissue apical to the root fracture most often remains unaffected and vital in nearly all cases (Cvek et al., 2008). By contrast, signs of early pulpal calcification can often be seen on follow-up radiographs which may be interpreted as a reaction of a vital apical pulp to the injury.

Root canal treatment, if necessary, should be limited to the coronal segment and follow the common guidelines. Due to the large size of the canal at the fracture site in the coronal fragment, 'working length' determination, cleaning and shaping as well as canal filling may be challenging, and it is recommended to use suitable strategies, similar to the treatment of immature teeth. In the rare cases that present with a lesion around the apical fragment, a combined treatment approach with root canal treatment of the coronal segment as outlined above and subsequent surgical removal of the apical fragment or extraction of the whole tooth and subsequent replantation of the root canal-treated coronal part are possible treatment strategies.

Shaping and filling both the coronal and the apical root canal by penetrating the tissue present in the fracture is unreliable and cannot be recommended.

The prognosis of teeth with intra-alveolar fractures following root canal treatment is favourable. Tooth survival has been reported to average 72% (fracture mid-root) or 67% (fracture apical), respectively, within an observation time of 8 years (Andreasen et al., 2012a). The overall survival rate of teeth with root fractures including endodontically treated teeth has been reported to approach 88% when teeth with cervical fractures are excluded as these teeth are often extracted due to an excessive mobility and a decreased resistance of the coronal fragment to a new impact (Cvek et al., 2008). There is only scarce data on pulp survival within the coronal fragment for concomitant crown fractures with exposed pulp. Cvek et al. (2004) described five teeth with root fractures whose pulps survived following partial pulpotomy. Endodontic therapies aiming at revascularization or revitalization of the diseased coronal pulp tissue have only been presented in a few cases so far (Saoud et al., 2016).

ENDODONTIC MANAGEMENT FOLLOWING ROOT FRACTURES: FUTURE DIRECTIONS

Hard tissue fusion of the fragments is regarded as the most favourable type of healing because the mobility of the coronal fragment is effectively reduced (Andreasen et al., 2012b). However, there is no clear evidence on how this pattern of healing is most likely to be achieved. With regard to the type of splint, current guidelines suggest a flexible splint for teeth with root fractures (Bourguignon et al., 2020) based on a retrospective study of 400 root-fractured teeth, which reported the highest frequency of favourable healing outcomes when Kevlar fibre splints were used (Andreasen et al., 2004b). This type of splint was classified as flexible. However, considering that the used fibres were completely embedded in cured resin after polymerization, the extent of flexibility achieved with this splint may be questionable. Laboratory studies have demonstrated that covering flexible splints with flowable composite increased splint rigidity (Franz et al., 2013). Thus, clear evidence is missing, whether splinting of root-fractured teeth should strictly follow the principles promoted for luxated teeth using highly flexible splints or if more favourable healing results can be achieved with increased splint rigidity. Regarding the splinting time, a recent paper suggests that long-term splinting may favour hard tissue deposition but clear evidence supporting this is missing (Isaksson et al., 2021).

Therefore, further studies focusing on type and duration of splinting after root fractures are warranted.

ENDODONTIC MANAGEMENT FOLLOWING LUXATION INJURIES: PRESENT STATUS

Through mechanical trauma following luxation injuries, the pulp can be subjected to tension, compression or separation at the apical constriction. The main parameters influencing pulp survival are the type and severity of the luxation injury as well as the width of the apical foramen.

Pulp repair may occur in immature teeth, with a return of sensibility within weeks to months (Andreasen, 1970, 1989; Andreasen & Vestergaard-Pedersen, 1985; Andreasen et al., 1986). Several radiographic signs indicate pulpal healing. Continued root development and pulp canal obliteration (PCO) indicate the reestablishment of the vascular supply of the pulp (Andreasen et al., 1987; Bastos & Cortes, 2018; McCabe & Dummer, 2012). Transient apical breakdown is a rare finding (4.2%) in which a transient apical radiolucency initially occurs and resolves within months to years, partially together with a gradually vanishing grey discolouration (Andreasen et al., 1986). Additional crown fractures with exposed dentinal tubules are a negative co-factor in the healing of a traumatized pulp (Lauridsen et al., 2012a, 2012b, 2012c). Dentinal fluid from a healthy pulp flows out of the open tubules at the fracture site. However, if the blood circulation is reduced or lost, necrotic tissue dissolution generates negative osmotic pressure inside the pulp chamber resulting in an inflow of saliva (and bacteria) into the tubules (Andreasen, 1995; Stenvik et al., 1972). Thus, the necrotic pulp tissue becomes infected and healing is impossible. The younger the patient, the larger the diameter of the dentinal tubules which means the pulp is more prone to infection. Other sources of infection are open dentine tubules in the cervical region or an infected blood clot in the socket (Cvek et al., 1990b). Apart from their undoubted benefits, fixed splints have to be seen as plaque accumulators. Therefore, similar to orthodontic treatment, appropriate oral hygiene instructions should be given including the recommendation of an antiseptic mouth rinse.

In teeth with fully formed roots and severe traumatic displacement of the tooth from its original position, pulp necrosis, followed by root canal infection and apical periodontitis is a common finding (Humphreys et al., 2003).

Additionally, in cases with considerable traumatic mechanical damage to the cementoblast layer on the root surface (particularly severe intrusions), external infection-related root resorption (EIR) may be an inevitable consequence (Kenny et al., 2003).

Thus, the endodontic management after luxation injuries varies between two extremes. On the one hand, root canal treatment should not be initiated if preservation of the pulp is a realistic scenario and revascularization of a damaged pulp is likely to occur. On the other hand, an early endodontic intervention is crucial in cases of high risk of developing EIR. This applies particularly for severe intrusions. At advanced stages of root formation, repositioning of the intruded teeth is usually necessary to obtain access to the root canal. Whilst there is no clear evidence whether the repositioning strategy (immediate surgical repositioning or orthodontic repositioning) has an influence on the survival of intruded teeth (Andreasen & Vestergaard-Pedersen, 1985; Costa et al., 2017), from an endodontic perspective, a repositioning method which allows early adequate root canal treatment is preferable. In the absence of root canal infection, the severely damaged root surface may still be prone to resorption; however, replacement resorption will emerge instead of EIR. It is beyond the scope of this review to go into further details on the management of teeth with replacement resorption and ankylosis.

During the follow-up visits, a number of signs indicate infected pulp necrosis; however, due to the ischaemic mechanism of pulp necrosis in luxation injuries, most patients do not have pain or swelling. Tenderness to percussion is found only in teeth with acute periapical inflammation. The presence of two of the three main symptoms (discolouration, negative sensibility, increasing periapical radiolucency) justifies endodontic intervention (Andreasen & Andreasen, 2007; Jacobsen, 1980). Further clinical signs may include a fistula/sinus tract, mucosal swelling, formation of an abscess or persistent mobility. In immature teeth, arrest of root development indicates (infected) pulp necrosis. Rapid EIR mainly occurs after intrusion and is a rare finding in the other types of luxation injuries (Andreasen & Vestergaard-Pedersen, 1985).

Last but not least, regular follow-ups are needed to ensure the current pulpal diagnosis was made correctly, especially in cases with PCO and/or negative sensibility.

Follow-ups, including clinical and radiographic examination are recommended at least 2, 4, 6–8 weeks, 3, 6 months, 1 year after trauma and annually for 5 years post trauma.

In doubt, shorter intervals should be chosen (Bourguignon et al., 2020).

If root canal treatment is indicated, the treatment of immature teeth with non-vital pulps remains challenging. Mechanical removal of root dentine from the thin root canal walls during instrumentation should be limited to a minimum. Instead, the focus lies on copious irrigation using sodium hypochlorite to remove necrotic pulp tissue and disinfect the root canal (Trope, 2006). Irrigant activation improves the cleansing effect and is therefore highly recommended (Caputa et al., 2019; Swimberghe et al., 2019). Apexification procedures with long-term calcium hydroxide dressing in teeth at early stages of root formation have a high risk of cervical root fracture (Cvek, 1992) and should therefore be avoided. Both the apical barrier technique with HCSC and revitalization are currently recommended procedures. The apical barrier technique has high success rates in terms of periapical healing ranging between 81% and 96% (Bonte et al., 2015; Bücher et al., 2016; Mente et al., 2009; Moore et al., 2011; Pace et al., 2014; Simon et al., 2007; Witherspoon et al., 2008) but only a few studies report long-term data after 8 to 10 years (Pace et al., 2014; Ree & Schwartz, 2017).

The success rates after revitalization are comparable to the apical plug technique but long-term data is missing for this protocol (Kahler et al., 2017). Currently, adverse events such as discolouration or the necessity to change the treatment option may be more likely after revitalization, but further root maturation may occur, even though the results regarding root lengthening and thickening are variable and not predictable (Kahler et al., 2017).

Another concern is that a potential increase of root thickness is usually limited to apical and mid-root areas, but not the cervical area, which is the region most susceptible to root fracture. The treatment modality appears to be beneficial especially in teeth at earlier stages of root development (Kim et al., 2018).

ENDODONTIC MANAGEMENT FOLLOWING LUXATION INJURIES: FUTURE DIRECTIONS

In cases of pulp necrosis following luxation injuries, further clinical research comparing the apical barrier technique with revitalization procedures is advocated to generate evidence on which treatment approach can provide the best long-term success.

Since the presence of cells of the apical papilla and of Hertwig's root sheath influences tissue ingrowth and healing, damage to these structures might jeopardize revitalization.

Thus, the influence of the type and the severity of luxation injuries on the outcome of revitalization procedures should be evaluated in clinical studies in order to provide clear recommendations for revitalization after different traumatic scenarios.

Whilst pulp necrosis can be treated with one of the abovementioned approaches, there is no reliable method of treating ankylosis-related root resorption which is one of the major threats of teeth affected by severe luxation injuries, particularly intrusions. Therefore, the development of pharmaceutical treatment strategies, either by internal application in the root canal or by external application and treatment of the root surface is desirable. From an endodontic perspective, alternative anti-resorptive intracanal medicaments which might help to promote periodontal healing should be investigated in clinical studies (see also: Endodontic management following avulsion: future directions).

ENDODONTIC MANAGEMENT FOLLOWING AVULSION: PRESENT STATUS

Avulsion of a tooth inevitably leads to necrosis of the disrupted pulp. Replantation is the treatment of choice for all permanent teeth. In mature teeth (with closed root apex), revascularization cannot occur after replantation. Instead, regardless of whether the crown is intact or not, bacteria contaminating the root surface or the intra-alveolar blood clot will enter the necrotic pulp tissue (Cvek et al., 1990a) and infection of the pulp space is believed to be established as early as 2–3 weeks after replantation (Tronstad, 1988). There is consensus that in mature teeth, early root canal treatment is mandatory and should be initiated within the first 2 weeks postreplantation in order to prevent EIR (Fouad et al., 2020). Calcium hydroxide or an antibiotic-corticosteroid paste can be used as intracanal medication. Based on the assumption that calcium hydroxide may impair initial periodontal healing due to diffusion of hydroxyl ions through dentinal tubules to the root surface (Lengheden, 1994; Lengheden & Jansson, 1995), it has been recommended to schedule the initiation of root canal treatment to 7–10 days after replantation (Andersson et al., 2012) in order to await the initial healing processes on the one hand, but to initiate treatment before pulp space infection is established on the other hand. However, the diffusion of calcium hydroxide through the dentinal tubules is limited by the buffering capacity of dentine and the presence of intact root cementum (Nerwich et al., 1993) and therefore, a clinically significant change in the pH on the root surface might not occur (Fuss et al., 1996). In any case, EIR can be prevented reliably if root canal treatment is initiated within 2 weeks postreplantation (Fouad et al., 2020). Depending on the severity of periodontal damage caused during extraoral storage, either periodontal healing or tooth ankylosis can be expected (Kenny et al., 2003; Lauridsen et al., 2019). To increase the survival of teeth and achieve periodontal healing following replantation, immediate placement of alternative intracanal medicaments containing an antibiotic-corticosteroid paste, such as Ledermix (Riemser) or Odontopaste (Australian Dental Manufacturing) have been proposed (Trope, 2011). After experimental avulsion and replantation in animal trauma models, this treatment approach was reported to promote favourable periodontal healing and reduce root resorption (Bryson et al., 2002; Wong & Sae-Lim, 2002). In a randomized controlled trial, a higher proportion of replanted teeth had periodontal healing if treated with Ledermix (8/12 teeth) compared to calcium hydroxide (6/15 teeth). However, there was no significant difference between the medicaments with $p = .17$. Ankylosis developed in the failing cases (Day et al., 2012).

In contrast to calcium hydroxide, Ledermix may be placed immediately or shortly following replantation (Andersson et al., 2012). Its main preventive mechanism against root resorption does not rely on an anti-bacterial effect, but on the direct inhibition of odontoclasts by detaching the resorbing cells from the root surface (Pierce et al., 1988b). Although both the steroid- (triamcinolone acetonide) and the tetracycline (demeclocycline hydrochloride) component in Ledermix have antiresorptive properties, a similar effect was demonstrated when triamcinolone was used alone after delayed replantation of teeth (Chen et al., 2008). Thus, Odontopaste (Australian Dental Manufacturing), which uses clindamycin as a substitute for the stain-inducing tetracycline component, but shares the same steroid component, is regarded as a reasonable non-staining alternative to Ledermix (Dettwiler et al., 2016).

In teeth with wide-open apices, the treatment approach is directed towards the re-establishment of a blood supply as these teeth may have the potential to revascularize and continue their root development (Trope, 2011). However, natural revascularization should only be considered as an option, if the individual rescue chain (storage conditions of the avulsed tooth) suggests that there is a reasonable chance of periodontal healing (Trope, 2011). In a dog model, it has been demonstrated that revascularization of the pulp in replanted immature teeth mainly occurs by ingrowth of newly formed blood vessels, which was visualized by microangiography in the entire pulp 30 days post replantation in most cases (Skoglund et al., 1978). The revascularization process is influenced by the size of the apical foramen, particularly by the length of the root, and can only occur in the absence of bacteria (Andreasen et al., 1995a). The longer the root, the greater is the distance to be revascularized and therefore the greater the chance of infection and the risk of EIR (Andreasen et al., 1995a). The likelihood of natural revascularization may exceed 40% under ideal conditions with an apical foramen greater than 2.75 mm and a pulp length less than 17 mm but may drop below 10% in immature roots with a distance to be revascularized of more than 19.5 mm (Andreasen et al., 1995a). Topical treatment of the root surface with doxycycline before replantation may be performed to increase the likelihood of natural revascularization (Cvek et al., 1990a) even though evidence from clinical studies is missing (Tsilingaridis et al., 2015). Systemic treatment with doxycycline failed to prevent or eliminate the contamination of the necrotic pulp tissue with microorganisms and therefore had no effect on the frequency of pulp revascularization (Cvek et al., 1990b). Nevertheless, the prescription of systemic doxycycline may be justified to promote periodontal healing in avulsed teeth according to the current guidelines (Fouad et al., 2020; Hinckfuss & Messer, 2009).

In general, after replantation of immature teeth, the risk of EIR should be balanced against the chance of revascularization (Fouad et al., 2020). Thus, frequent follow-ups are mandatory for early detection of pulp necrosis and EIR if revascularization is attempted but fails.

ENDODONTIC MANAGEMENT FOLLOWING AVULSION: FUTURE DIRECTIONS

The main goal in the treatment of avulsed teeth is periodontal healing which is mainly influenced by the storage conditions before replantation. Whilst the benefit of systemic and topical medicaments is very limited, the greatest potential may still be the application of suitable medicaments in the root canal to maintain a therapeutic level of anti-clastic medicaments to the periradicular area to promote periodontal healing. Future research should aim to confirm the favourable data from animal studies in clinical studies with a sufficient number of patients.

In replanted teeth with open apices, natural revascularization is regarded as the most favourable outcome, but there is scarce evidence on how this goal can be best achieved. Topical treatment of the root surface with doxycycline or minocycline before replantation has been reported to significantly increase the frequency of complete pulp revascularization in animal studies by decreasing the frequency of microorganisms in the pulpal lumen (Cvek et al., 1990a; Ritter et al., 2004). However, in a retrospective case–control study with a small number of patients, this effect could not be proven (Tsilingaridis et al., 2015). Therefore, more clinical evidence on this topic is necessary. An additional approach to render the necrotic pulp free of bacteria might include retrograde infiltration of the pulp with antibiotics before replantation.

ENDODONTIC MANAGEMENT IN CASES OF EXTERNAL INFECTION-RELATED RESORPTION (EIR): PRESENT STATUS

Infection-related root resorptions (also referred to as inflammatory root resorptions) pose the biggest threat for teeth with severe luxation injuries (mainly avulsion and intrusion). They are initiated by a combination of severe damage to the protective cementum layer on the root surface and pulp space infection which is facilitated by the missing (avulsion) or considerably damaged (intrusion) neurovascular supply of the pulp tissue. Even if the crown is intact, bacteria may enter a necrotic pulp through exposed dentinal tubules or enamel-dentine cracks as early as 2–3 weeks after trauma (Andreasen, 1981; Tronstad, 1988). Once the pulpal infection is established, external root resorption is maintained by microorganisms and their toxins, which enter the inflammatory process in the PDL via open dentinal tubules after loss of the barrier function of the root cementum (Trope, 2002).

Apart from the lack of response to pulp tests, teeth with EIR usually do not have any clinical signs of disease and therefore, EIR is most often diagnosed only radiographically. Affected teeth are characterized by bowl-shaped radiolucencies along the root surface and corresponding defects in the adjacent alveolar bone. Numerous studies have reported the limitations of 2D radiography and demonstrated that CBCT is more accurate in detecting EIR particularly in its early stages (Patel et al., 2015). Nonetheless, a CBCT examination cannot be recommended for routine monitoring of teeth at risk for root resorption, particularly in children, whose tissues are especially sensitive to the effects of ionizing radiation (Whitworth, 2018). After being asymptomatic for the first weeks, teeth with EIR may at later stages present with increased mobility, dull percussion sound, sensitivity to percussion or with a sinus tract at later stages.

In teeth with closed apices at risk of root resorption due to severe luxation injuries, EIR can be reliably prevented by timely initiation of root canal treatment within the first 2 weeks after trauma. Unfortunately, due to inadequate endodontic management, EIR is a frequently encountered sequel in clinical practice (Andreasen et al., 1995b). Moreover, in teeth with open apices, a treatment approach intended to induce natural revascularization and promote further root formation is usually adopted. If revascularization fails in these cases, EIR can cause complete root destruction within a few months (Tronstad, 1988; Trope, 2002). Therefore, early detection of EIR is crucial because tooth preservation is unpredictable if large parts of the root are already affected.

In teeth at high risk of EIR, the first follow-up radiographs should be performed 2, 4 and 6 weeks after trauma to identify the first radiologic signs (small radiolucencies along the external root surface of the dentine and adjacent bone), which may be already visible at these time points (Patel et al., 2016). Standardization of these radiographs facilitates the early identification of EIR. To arrest EIR, the elimination of the microorganisms from the root canal system is crucial and involves thorough canal debridement and irrigation with sodium hypochlorite. Activation of the irrigant promotes the removal of pulp tissue remnants and hard tissue debris (Caputa et al., 2019; Swimberghe et al., 2019) and is therefore highly recommended. Smear layer removal with chelators such as EDTA is beneficial to facilitate the diffusion of intracanal medicaments through dentine to the external root surface (Heithersay, 2007; Tronstad et al., 1981). The standard approach for root canal medication is placement of a calcium hydroxide dressing. It has been demonstrated that the diffusion of calcium hydroxide through the dentinal tubules significantly increased the pH in resorption areas, where cementum was not present (Tronstad et al., 1981). Thus, besides the antibacterial and endotoxin-neutralizing effect in the root canal, calcium hydroxide has the potential to favourably influence the local environment at the resorption sites through inactivation of acids and collagenases which are released from the clastic cells. Furthermore, root surface repair might be promoted through stimulation of alkaline phosphatases by the alkaline pH at the resorption sites (Tronstad, 1988). However, evidence supporting this widespread assumption is missing. An animal study demonstrated that long-term intracanal medication with calcium hydroxide for 3 months was more effective than short-term application for 1 week for the treatment of established EIR (Trope et al., 1995). Clinically, high success rates in terms of healing or arrest of the resorption, have been demonstrated following medication with calcium hydroxide from 3 to 54 months (mean value for immature teeth was 24 months and for mature teeth 11 months) (Cvek, 1992). However, there is no consensus on whether long-term calcium hydroxide dressing up to the point when there is radiographic evidence of resorption control is needed in cases of established EIR (Patel et al., 2016; Whitworth, 2018). The recommendations for the duration of calcium hydroxide medication vary between 4 weeks (Darcey & Qualtrough, 2013) and several months (Trope, 2002). An alternative approach for treating established EIR involves the use of antibiotic-corticosteroid combinations such as Ledermix (Riemser) or Odontopaste (Australian Dental Manufacturing) for eliminating the inflammatory reaction in the periodontal membrane (Heithersay, 2007; Pierce & Lindskog, 1987). Likewise, an animal study suggested the intracanal use of calcitonin as an adjunct in the treatment of EIR (Pierce et al., 1988a) but clinical studies are missing. A few case reports have used regenerative endodontic procedures for treating teeth with EIR (Chaniotis, 2015; Lu et al., 2020; Santiago et al., 2015; Saoud et al., 2016; Tzanetakis, 2018; Yoshpe et al., 2020); however, there is insufficient evidence to support this approach for routine clinical practice in such cases.

After successful arrest of EIR, depending on the degree of trauma-induced PDL damage, periodontal healing may occur, or the process may develop into ankylosis.

ENDODONTIC MANAGEMENT IN CASES OF EXTERNAL INFECTION-RELATED RESORPTION (EIR): FUTURE DIRECTIONS

The prognosis of teeth with EIR mainly depends on their early detection so that root canal treatment can be initiated as early as possible. However, small initial resorptive lesions are difficult to detect on 2-dimensional radiographic images, particularly on the buccal and palatal aspect of the root. Artificial intelligence (AI) is increasingly being used to improve diagnosis in different fields of clinical dentistry (Reyes et al., 2021). AI algorithms may be a valuable tool for monitoring traumatized teeth at high risk of developing EIR and for detection of initial radiologic signs of EIR.

Even though EIR is primarily a radiologic diagnosis, a clinical diagnostic approach seems conceivable. Two recent studies identified IL-1α in the gingival sulcus fluid of affected teeth as a potential biomarker for EIR (Gregorczyk-Maga et al., 2019, 2021). Further research is needed to evaluate the clinical usefulness of biomarker-based diagnostic tests for this specific type of root resorption.

Whilst the treatment of teeth with infection-related resorption primarily relies on disinfection of the root canal, there is no evidence whether the use of antiresorptive corticosteroid or hormone dressings in the root canal (possibly followed by calcium hydroxide) increase the likelihood of successful periodontal healing compared to the use of calcium hydroxide alone. Therefore, clinical studies evaluating this effect are needed. Likewise, clinical evidence is needed to assess whether regenerative endodontic procedures can be recommended for the treatment of teeth with infection-related resorption.

ENDODONTIC MANAGEMENT IN CASES OF INTERNAL RESORPTION (IR): PRESENT STATUS

Internal progressive root resorption ('internal ganuloma') is a rare endodontic complication after trauma but other initiating factors such as invasive crown preparation of teeth with vital pulps or chronic pulpal inflammation are also discussed (Haapasalo & Endal, 2006; Trope et al., 2016). Although the aetiology is not fully understood, it has been suggested that intrapulpal haemorrhage and localized compression resulting from a blow might lead to death of odontoblasts and damage of the resorption-resistant non-mineralized predentin layer in the affected area of the root canal (Whitworth, 2018). As a result, the mineralized tissue becomes exposed to pulpal cells with resorbing potential. The resorptive process is stimulated by the presence of bacteria in the necrotic pulp coronal to the resorption, whilst the pulp tissue at and apical to the resorption area is vital. Thus, the process can be interpreted as a defensive reaction of sound apical pulp tissue against its necrotic and infected coronal part. The multinuclear clastic cells in the highly vascularized resorption tissue induce a symmetric expansion of the pulp canal which can result in perforation of the root at later stages (Haapasalo & Endal, 2006). The resorptive process will only cease if pulp necrosis of the apical pulp cuts of the nutritional supply for the resorbing cells or if endodontic intervention is initiated.

A special form of internal resorption is internal replacement resorption. In such cases, the resorptive process within the root is accompanied by a reparative process that results in the deposition of metaplastic bone/cementum-like tissues in the resorption area (Patel et al., 2010).

In general, root canal treatment is regarded as the treatment of choice for internal resorption. Before starting treatment, it must be ensured that the diagnosis is correct, since external invasive cervical resorption is often misdiagnosed as internal resorption (Patel & Ford, 2007). It is beyond the scope of this review to address this different type of resorption which has extensively been discussed in various articles (ESE, 2018).

Root canal treatment of teeth with internal resorption should follow the conventional guidelines. Copious irrigation using sodium hypochlorite and activation of the irrigant is crucial to remove any necrotic pulp tissue and ensure adequate disinfection of the internal resorption defect.

Complete filling of the resorptive defect is best achieved with thermoplastic gutta-percha techniques or with HCSCs in case of perforation (Patel et al., 2010).

ENDODONTIC MANAGEMENT IN CASES OF INTERNAL RESORPTION (IR): FUTURE DIRECTIONS

The drawback of the conventional endodontic treatment approach for cases of internal resorption is that the weakened root remains susceptible to spontaneous fracture after root canal filling. To address this problem, a promising regenerative treatment alternative has been suggested (Ebeleseder & Kqiku, 2015). The authors have impressively shown that disinfection and application of calcium hydroxide in the space coronal to the resorptive site, turns the granuloma into a calcifying hard tissue which is able to restore the defect in the root. Thus, not only the weak root is strengthened but also the tooth is preserved with a vital pulp. Recent case reports with a comparable approach confirmed the feasibility of this treatment even for severe cases where preoperative CBCTs demonstrated perforation of the root surface (Arnold, 2021; Kaval et al., 2018) but valid clinical data on the success rates is needed.

CONCLUSION

The pulp plays a central role in the management of traumatized teeth and significantly influences their longevity, particularly in severe cases. There is a need for future research to pay greater attention to (1) diagnostic methods to assess the perfusion of the pulp and enhance detection of tooth cracks and initial signs of root resorption; (2) improved materials for vital pulp treatment; (3) studies focusing on type and duration of splinting after root fractures; (4) antiresorptive intracanal medication in case of posttraumatic pulp necrosis and infection-related resorption and (5) long-term data on the apical barrier technique compared to revitalization.

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CONFLICT OF INTEREST

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AUTHOR CONTRIBUTION

Gabriel Krastl: Conceptualization, writing, review and editing (lead). **Roland Weiger:** writing, review and editing. **Kurt Ebeleseder:** writing, review and editing. **Kerstin Galler:** writing, review and editing.

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