Received: 1 November 2021 | Accepted: 4 March 2022

DOI: 10.1111/iej.13723

INTERNATIONAL ENDODONTIC JOURNAL | WILEY

REVIEW ARTICLE

Present status and future directions: Surgical extrusion, intentional replantation and tooth autotransplantation

Gianluca Plotino[1] | **Francesc Abella Sans**[2] | **Monty S. Duggal**[3] | **Nicola M. Grande**[4] | **Gabriel Krastl**[5] | **Venkateshbabu Nagendrababu**[6] | **Gianluca Gambarini**[1]

[1]Department of Endodontics, 'Sapienza' – University of Rome, Rome, Italy

[2]Department of Endodontics, Universitat Internacional de Catalunya, Barcelona, Spain

[3]College of Dental Medicine, QU Health, Qatar University, Qatar, Doha

[4]Department of Endodontics, Catholic University of Sacred Heart, Rome, Italy

[5]Department of Conservative Dentistry and Periodontology and Center of Dental Traumatology, University Hospital of Würzburg, Würzburg, Germany

[6]Department of Preventive and Restorative Dentistry, University of Sharjah, Sharjah, UAE

Correspondence
Gianluca Plotino, Via Calabria 25, Rome 00187, Italy.
Email: endo@gianlucaplotino.com

Abstract

Surgical extrusion, intentional replantation and tooth autotransplantation procedures are important treatment options that clinicians may consider performing in their day-to-day clinical practice. Despite compromised teeth are generally considered for extraction, clinicians must be aware that these cases could be suitable for management by these alternative predictable treatment options. Surgical extrusion, intentional replantation or tooth autotransplantation have similar treatment protocols which includes atraumatic tooth extraction, visualisation of the root portion and replantation. Surgical extrusion is defined as the 'procedure in which the remaining tooth structure is repositioned at a more coronal/supragingival position in the same socket in which the tooth was located originally'. Intentional replantation is defined as the 'deliberate extraction of a tooth and after evaluation of root surfaces, endodontic manipulation and repair, placement of the tooth back into its original position'. Tooth autotransplantation is defined as the 'transplantation of an unerupted or erupted tooth in the same individual, from one site to another extraction site or a new surgically prepared socket'. The same team previously published a narrative review (*International Endodontic Journal*. 2020, 53, 1636) and European Society of Endodontology position statement (*International Endodontic Journal*. 2020, 54, 655) on this topic in *International Endodontic Journal*. The aim of the current updated review was to provide the reader a complete overview and background on these procedures, to established clear clinical protocols and step-by-step for technically perform these therapies in their clinical practice and to establish future directions on the topics. The clinicians must periodically update their knowledge about these three procedures to achieve success.

KEYWORDS

intentional replantation, review, root canal, surgical extrusion, tooth transplantation

BACKGROUND AND OVERVIEW

Procedure	Definition
Surgical extrusion	Intra-alveolar transplantation to make unrestorable teeth restorable through intentional coronal displacement of the remaining root within the socket (Tegsjõ et al., 1978).
Intentional replantation	Surgical procedure to primarily treat inaccessible endodontic or resorptive lesions through intentional atraumatic extraction, extra-oral repair and subsequent reinsertion of the tooth into the extraction socket (Bender & Rossman, 1993).
Tooth autotransplantation	Surgical procedure to replace hopeless teeth through transfer of an impacted or erupted tooth from a donor site to an extraction or surgically prepared recipient site (Natiella et al., 1970).

Surgical extrusion

Surgical extrusion is considered as a treatment of last resort for unrestorable teeth with fractures or carious decay of the crown in proximity to the bone level (Kelly et al., 2016). This surgical approach, also referred to as intra-alveolar transplantation, involves the intentional repositioning of the remaining root portion within the socket to a more coronal position to obtain sufficient ferrule and restorability (Das & Muthu, 2013; Kahnberg, 1985).

Complete extraction from the socket may be performed to evaluate the integrity of the root structure before replantation and to detect potential additional fractures that would preclude any attempt to preserve the affected tooth. The success of surgical extrusion therapy is mainly based on a minimal invasive extraction with minimal damage to the cementoblast layer on the root surface (Oikarinen et al., 1996). Surgical extrusion treatment outcome is considered successful when periodontal healing is present, without root resorption or ankylosis. Nevertheless, in patients who have achieved physical maturity, ankylosis may be considered as an acceptable outcome, as root resorption in such cases progresses slowly and does not lead to significant infraposition and arrested alveolar bone growth, as would occur in a patient still in the phase of active growth (Krug et al., 2018b). However, age did not seem to have an impact on the results (Krug et al., 2018a). A favourable outcome also includes the presence of a stable marginal bone level without significantly increased tooth mobility (Elkhadem et al., 2014). Two systematic reviews, including most of the clinical studies that evaluated the success rates of surgical extrusion over the last four decades, have concluded that this treatment should be considered an important technique for managing teeth with subgingival fractures or caries (Das & Muthu, 2013; Elkhadem et al., 2014). These reviews have also demonstrated good periodontal healing and maintenance of marginal bone height and rare signs of ankylosis and root resorption.

Published in 1978, the first case report of surgical extrusion, described the exposure of the apical third of a tooth with a subgingival fracture by removing the bone to gain access to the tip of the root (Tegsjo et al., 1978). The root was luxated with a special crown remover that was placed at the apex in order to move the root coronally to the desired position using only axial forces. Subsequently, Tegsjo et al. (1987) and Kahnberg et al. (1982) reported a positive outcome of a case series. However, concerns over possible apical root resorption resulting from the rather invasive technique were raised and the need for bone transplants to support the root and prevent relapse was questioned (Kahnberg, 1985).

Further clinical studies demonstrated a lower incidence of apical root resorption extrusion by using a simplified extraction technique consisting of careful root mobilization using elevators and cutting of marginal periodontal fibres with a sharp carver, but with no apical bone transplant (Caliskan et al., 1999; Kahnberg, 1985, 1988, 1996; Warfvinge & Kahnberg 1989). The histologic evaluation of the root surfaces in dog teeth showed functional repair with normal periodontal ligament (PDL) and no ankylosis after 120 days (Kim et al., 2009).

Furthermore, an animal study in monkeys showed that, when using forceps for extraction with only rotational movements to reduce the risk of root resorption, mechanical damage to the PDL could not be entirely avoided. This is particularly relevant in cases with reduced coronal tooth structure, such deep fractures (Oikarinen et al., 1996). Since root cross-sections rarely depict circular cross-sections, and corner surfaces of the root are more compressed during tooth removal, cementoblast loss and root resorption occur in these specific areas. A histometric analysis showed that conventional forceps cause significantly more cementoblast loss than instruments specially designed for vertical tooth extraction (Oikarinen et al., 1996).

Minimally invasive vertical tooth extraction techniques enable the extraction of badly damaged teeth without the need for flap surgery and to reduce the extent of alveolar bone resorption (Hong et al., 2018; Muska et al., 2013; Saund & Dietrich, 2013). Atraumatic extraction systems deliver extrusive forces directed along the long axis of the root and minimizes damaging lateral forces. The first implementation of the minimal invasive approach for surgical extrusion was reported to facilitate the restoration

of a severely decayed premolar (Kelly et al., 2016). This technique is also considered a recognized approach for a predictable and minimal invasive extrusion without socket expansion (Dietrich et al., 2019). A recent clinical study demonstrated successful vertical extrusion of 51 severely compromised teeth that would otherwise have been considered as unrestorable (Krug et al., 2018a). Even though surgical extrusion is considered a feasible treatment approach for unrestorable teeth, a balanced risk–benefit analysis, including other alternatives such as surgical crown lengthening or orthodontic extrusion (forced eruption), is recommended.

Intentional replantation

Intentional replantation is a procedure that involves the extraction of a tooth, followed by assessing the root surfaces, endodontic manipulation and repair, placing the tooth back into its original socket (Bender & Rossman, 1993; Grossman, 1966). It differs from surgical extrusion as the tooth is placed at the same bone level as it was before extraction without repositioning it more coronally. Intentional replantation is a treatment option for various situations, like failed non-surgical root canal treatment and apical microsurgery, perforations and external root resorption, teeth with crown-root fracture, periodontally compromised teeth and periodontal defects due to radicular grooves and cases in which the patient cannot afford longer and/or more expensive treatments (Mainkar, 2017). Favourable conditions exist for single-rooted teeth where extraction may be performed without major damage to the root surface and without the risk of fracture. However, all precautions must be taken to prevent the root surface from drying out during the extra-oral manipulation.

Current advancement in apical microsurgery have provided solutions to some of the limitations of non-surgical root canal treatment (Chércoles-Ruiz et al., 2017). Nevertheless, some cases cannot be treated adequately with apical microsurgery, due to the surrounding anatomic structures (i.e., closeness to the mental nerve or maxillary sinus) and the difficult accessibility of certain sites such as the palatogingival groove. Hence, intentional replantation provides a solution with fewer complications for such scenarios (Choi et al., 2014; Garrido et al., 2016). Another key factor that must be considered is the patient's financial restrictions for conventional implant placement (Grzanich et al., 2017), leaving intentional replantation as a more cost-efficient way to preserve a natural tooth.

Intentional replantation has also been used as a method that allows extra-oral bonding of teeth with vertical root fractures (Hayashi et al., 2002, 2004; Nizam et al., 2016; Okaguchi et al., 2018; Rosen et al., 2018; Sugaya et al., 2016). It has also been used as a treatment option to treat teeth considered as having a periodontally poot prognosis (Hou et al., 2016; Saida et al., 2018; Solakoglu & Filippi, 2017).

The main advantage of this procedure is that the inaccessible areas of the tooth surface, can be directly viewed and repaired without damaging the adjacent periodontal tissues. However, many practitioners consider this as a last option, because of the possible damage to the PDL and the attendant consequences for external root resorption. The most recent published literature on this topic reports an extremely favourable clinical outcome, that is highly encouraging (Asgary & Roghanizadeh, 2018). Wu and Chen (2021) reported that intentional replantation procedure performed with the use of Emdogain to cover the root surface in certain patients, was a viable treatment of choice with 82.8% survival rate at four years. A systematic review with meta-analysis showed that survival rates of intentionally replanted teeth was approximately 90% (Torabinejad et al., 2015). As a consequence, when surgical/non-surgical retreatment is not feasible, intentional replantation is an alternative, reliable and cost-effective procedure (Mainkar, 2017).

Tooth autotransplantation

The principal indications for tooth autotransplantation procedure includes impacted or ectopic teeth, premature and/or traumatic tooth loss and tooth loss due to tumour or to iatrogenic reasons. This technique is equally viable for congenitally missing teeth in one arch combined with arch length discrepancy or clinical signs of tooth crowding in the opposite arch, replacement of teeth with poor endodontic and restorative prognosis, as well as cleft lip and palate and/or developmental dental anomalies (Almpani et al., 2015; Chung et al., 2014; Tsukiboshi, 2002). Therefore, autotransplantation could be considered as a versatile technique that can be used for several indications both in adolescents and in adults.

Distinct to the immovable osseointegrated dental implant, which impedes alveolar development in growing patients, autotransplanted teeth ensure vital periodontium and are compatible with the eruption process of adjacent teeth (Gilijamse et al., 2016; Park et al., 2010; Plakwicz et al., 2013). The long-term prognosis of tooth autotransplantation, principally with an immature donor tooth, is comparable to that of dental implants (Chung et al., 2014; Kafourou et al., 2017; Tsukiboshi, 2002). Studies on replanted and transplanted teeth have reported that immature young teeth have sufficient blood supply and stem cells to promote pulp revascularization following transplantation (Almpani et al., 2015; Atala-Acevedo

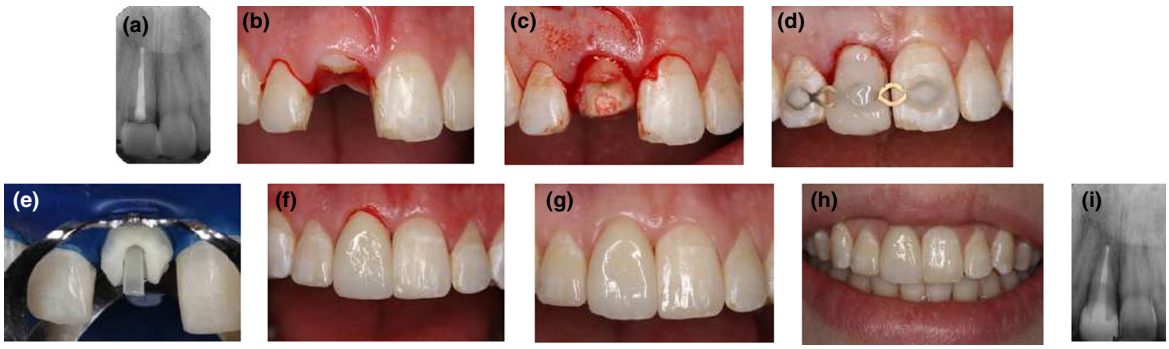

FIGURE 1 (a) Pre-operative radiograph. (b) Labial view showing crown-root fracture in the maxillary right central incisor. (c) Surgical extrusion: the root is extracted, replanted after 180° rotation. (d) Splinting done using composite and a flexible wire. (e) Restorative treatment performed with placement of a post. (f) Restoration immediately after rubber dam removal. (g) Clinical view at 6 months follow-up. (h) Smile of the patient. (i) Radiograph view at 6 months follow-up

et al., 2017; Kafourou et al., 2017; Kumar et al., 2013). This process takes place due to the growth of vascularized connective tissue into the pulp space or the anastomosis of both transplanted tooth blood vessels and periodontal blood vessels (Skoglund & Bjercke 1978, Skoglund & Tronstad, 1981). Pulp revascularization promotes continuous root development and tooth vitality. In addition, autotransplantation maintains the natural shape of attached gingiva, resulting in a good aesthetics (de Freitas Coutinho et al., 2021; Jang et al., 2016a). In the light of these benefits, autotransplantation of immature teeth is often the treatment of choice in young patients (Czochrowska et al., 2002; Mejàre et al., 2004).

There have also been reports of high success rates in mature teeth; consequently, autotransplantation procedure has become an additional treatment of choice in current rehabilitation strategies (Bae et al., 2010; Sugai et al., 2010; Yu et al., 2017). Although pulp healing would not be an expected healing outcome, periodontal healing should not be compromised while transplanting teeth with complete root development. Chung et al. (2014) reported that the projected 1- and 5-year survival rates of mature autotransplanted teeth were 98.0% and 90.5% respectively. Most of the adult donor teeth have a closed apex, which requires root canal treatment before, during or after transplantation procedure (Chung et al., 2014).

Favourable PDL healing is the key factor for success, regardless of whether teeth are mature or immature (Tsukiboshi, 2002). The PDL not only aids bone induction and prevents severe complications, such as replacement root resorption, but also allows the possibility of performing subsequent orthodontic tooth movement (Jonsson & Sigurdsson, 2004; Tsukiboshi, 2002). A traumatic extraction or trauma caused by inadequate socket preparation at the recipient site may mechanically damage PDL cells of the donor tooth, resulting in gradual root resorption. The PDL cells can also be bio-chemically damaged due to various extra-oral conditions, such as variable pH, osmotic pressure, dehydration (Andersson et al., 1989; Andreasen, 1981; Andreasen et al., 1995; Patil et al., 1994), making extra-alveolar time before placement into the new site an important prognostic factor of success.

The fabrication of a 3D tooth replica and 3D-printed guiding templates contribute to reducing possible mechanical damage to the PDL during extraction, reduce the extra-oral time of donor tooth, improve surgical preparation of the recipient site and reduce the potential damage to the PDL of the donor tooth (Anssari Moin et al., 2017; Lee et al., 2001; Strbac et al., 2016). Surgical planning software allows the clinician to select the most appropriate donor tooth according to tooth anatomy, design the ideal position of the donor tooth in 3D and calculate the required dimensions of the alveolus during surgery. In addition, the use of tooth replicas reduces the additional extra-oral socket time and reduces the number of fitting attempts before an optimum fit is obtained (Lee et al., 2001; Lee & Kim, 2012; Oh et al., 2018; Strbac et al., 2016), minimizing the chances of iatrogenic damage to the PDL (Anssari Moin et al., 2017). Recently, Strbac et al. (2020) presented a surgical technique using virtually preplanned 3D-printed templates for guided osteotomies to ensure a guided atraumatic approach and facilitate highly complex treatments.

When planning the ideal 3D position of the donor teeth for a successful transplantation, a sufficiently large recipient site is crucial (Kafourou et al., 2017; Tsukiboshi, 2002). However, conditions at the recipient site are not always optimum and may vary depending on when the tooth was lost (Zufía et al., 2017). In cases of transplantation to a fresh extraction site immediately after extraction of the hopeless tooth, sufficient bone is usually available (Lundberg & Isaksson, 1996; Mejàre et al., 2004). In cases of previous extraction with partial or complete regeneration of the alveolar socket, an adequate recipient site can usually be surgically created (Conklin, 1974; Yu et al., 2017).

The current evidence recommends autotransplanted teeth with complete/ incomplete root formation have favourable survival and success rates with less complications (Chung et al., 2014; Rohof et al., 2018). Various clinical studies have reported 80%–100% of survival rate (Almpani et al., 2015; Borring-Møller & Frandsen, 1978; Chung et al., 2014; Hernandez & Cuestas-Carnero, 1988; Kristerson, 1985; Kristerson & Lagerström, 1991; Kugelberg et al., 1994; Plotino et al., 2020; Rohof et al., 2018; Schatz & Joho, 1992; Slagsvold & Bjercke, 1978).

CLINICAL TECHNIQUES AND MATERIALS CURRENTLY AVAILABLE

Surgical extrusion (Figure 1)

Surgical extrusion is indicated in single-rooted permanent teeth with fractures or carious decay of the crown in proximity to the bone level, irrespective of the patient age. In general, after extrusion, the root should be long enough to provide adequate alveolar support and a favourable crown-to root ratio (Penny & Kraal, 1979). However, in special cases even the extrusion of short roots may be regarded as a success if temporary tooth preservation helps to postpone a dental implant until adulthood. Before treatment the patient or the legal guardian should be provided with specific information regarding the clinical procedure as well as the treatment alternatives.

Any carious dentine must be removed to assess the remaining tooth structure and to determine the intended amount of extrusion. After local anaesthesia, the gingival fibrous attachment is incised using a scalpel blade. During mobilization of the root, utmost care should be taken to avoid extensive mechanical damage of the root surface. In particular, the elevators should be used with gentle pressure. The cervical portion of the tooth can be grasped with a forceps using rotation movements. Preparation of a circumferential groove between the root and the surrounding bone with a tapered-point diamond rotary instrument may be considered to enable a firm grip of the forceps on the root (Angerame et al., 2021). For difficult cases a vertical extraction device can be recommended for an atraumatic extraction of the root (Dietrich et al., 2019). This can be the case when long roots such as canines need to be extruded and the use of elevators and forceps is not feasible due to completely missing coronal tooth structure. Furthermore, extraction in older patients appears more challenging than it is in children and adolescents due to a higher density of the alveolar bone and a decrease in the PDL space with age (Van der Velden 1984).

The clinical application of the Benex vertical extraction system (Benex; Helmut Zepf Medizintechnik GmbH) has been described in detail recently (Dietrich et al., 2019). Briefly, a screw hole is prepared in the root canal orifice with a diamond-coated drill. A matching self-tapping screw is anchored in the prepared root canal and connected to the extractor with a flexible pull rope. The extraction force is increased by slowly turning the handle of the extractor clockwise until rupture of dento-alveolar fibres will typically be indicated by mild bleeding from the sulcus and a drop in the tension in the pull rope. When the desired coronal position of the root is achieved, the screw is removed. Careful, visual inspection of the exposed root is highly recommended in order to detect any additional fractures.

Even though surgical extrusion with the Benex extraction system seems to fully prevent progressive root resorption and ankylosis, removal of sound hard tissues during preparation of the screw hole and a risk of perforation that cannot be completely ruled out may be regarded as possible drawbacks (Krug et al., 2018a). Further, insertion of the screw may induce dentinal cracks, thus potentially limiting the long-term prognosis of the tooth.

A typical indication for surgical extrusion is the management of teeth with crown-root-fractures. In maxillary anterior teeth, crown-root-fractures have a typical fracture line: on the labial side, the fracture is localized paragingivally or supragingivally, while palatally the defect often extends into the infraosseous root region. In contrast, the bone level of the alveolar process in the upper anterior region is more coronally on the palatal side compared to the labial side. For that reason, rotation of the root by 180 degrees before replantation is ideal to expose the defect margin on both aspects while minimizing the extrusion distance at the same time (Krastl et al., 2011). In case of surgically extruded maxillary premolars, rotation of the tooth by 180° did not seem to affect the clinical outcome (Choi & Lee, 2019).

A flexible splint allowing physiologic tooth mobility is applied to reduce the risk of ankylosis (Kahler et al., 2016). Due to mismatch between the socket and the extruded root the splinting period may be longer than that after replantation of avulsed teeth and can be extended up to 6 weeks, particularly in cases of high mobility of the extruded root (Kelly et al., 2016; Mohamed et al., 2021). Endodontic treatment should be initiated in accordance with the treatment of avulsed teeth within the first 2 weeks after replantation to avoid infection-related root resorption (Fouad et al., 2020; Krastl et al., 2021b). Within the first week, calcium hydroxide should be avoided as an intra-canal dressing due to a possible negative impact on periodontal healing if placed immediately after replantation (Lengheden 1994; Lengheden and Jansson 1995).

An antibiotic-corticosteroid paste such as Odontopaste (Australian Dental Manufacturing) is a good alternative since it may be placed following replantation and additionally acts as an anti-inflammatory and anti-clastic intra-canal medicament (Krastl et al., 2021a). The more commonly available Ledermix (Riemser) may cause discoloration of the teeth, which will have aesthetic implications. Extra-oral root canal treatment is usually not recommended because manipulation under dry conditions is likely to interfere with PDL cell viability and increase the risk for root resorption (Andreasen, 1981). However, in case of surgical extrusion of root-filled teeth, apicoectomy with retrograde sealing of the root canal may be considered.

Restorative treatment is usually performed 6 to 8 weeks after surgical extrusion. If crown placement is indicated, a biologically oriented preparation technique, as recently described, may be helpful to achieve an improved gingival architecture and greater long-term soft-tissue stability (Llaquet Pujol et al., 2021). Although systemic antibiotics were prescribed in some clinical reports on surgical extrusion, there is insufficient evidence to support or reject their use.

Intentional replantation (Figures 2 and 3)

A pre-operative CBCT can help in assessing the root anatomy (Akhlef et al., 2018; Shahbazian et al., 2010; Verweij et al., 2017). Whenever necessary it is recommended to perform the orthograde endodontic treatment before starting the intentional replantation procedures; this will help to get an affordable seal surgically, while performing intentional replantation procedure. A systematic review reported that systemic antibiotic prophylaxis (e.g. amoxicillin/clavulanic acid) might reduce the failure rate after intentional replantation (Chung et al., 2014).

It is recommended to perform local debridement of plaque and calculus before the surgical treatment (Becker, 2018). After local anaesthesia, an atraumatic extraction should be performed, thus avoid damaging the PDL cells present in the coronal portion of the root surface. Krug et al. (2019) reported that the use of atraumatic extraction has improved the outcome of intentional replantation in teeth with extensive cervical root resorption. To avoid damaging the gingival fibres, a sterile gauze can be placed on the tooth under the beaks of the extraction forceps. A

FIGURE 2 (a–d) Initial situation of a first left lower molar with absence of ferrule and pulp chamber floor perforation in which an intentional replantation with surgical extrusion and root separation was performed. (e) The splint was provided using a stainless-steel wire for 15 days. (f–g) The root canal treatment, fibre post-intracoronal restoration and methacrylate resin temporary crown were then performed. (h–j) The 6 years radiographic and clinical controls showed good periodontal health around the zirconia crown and normal function

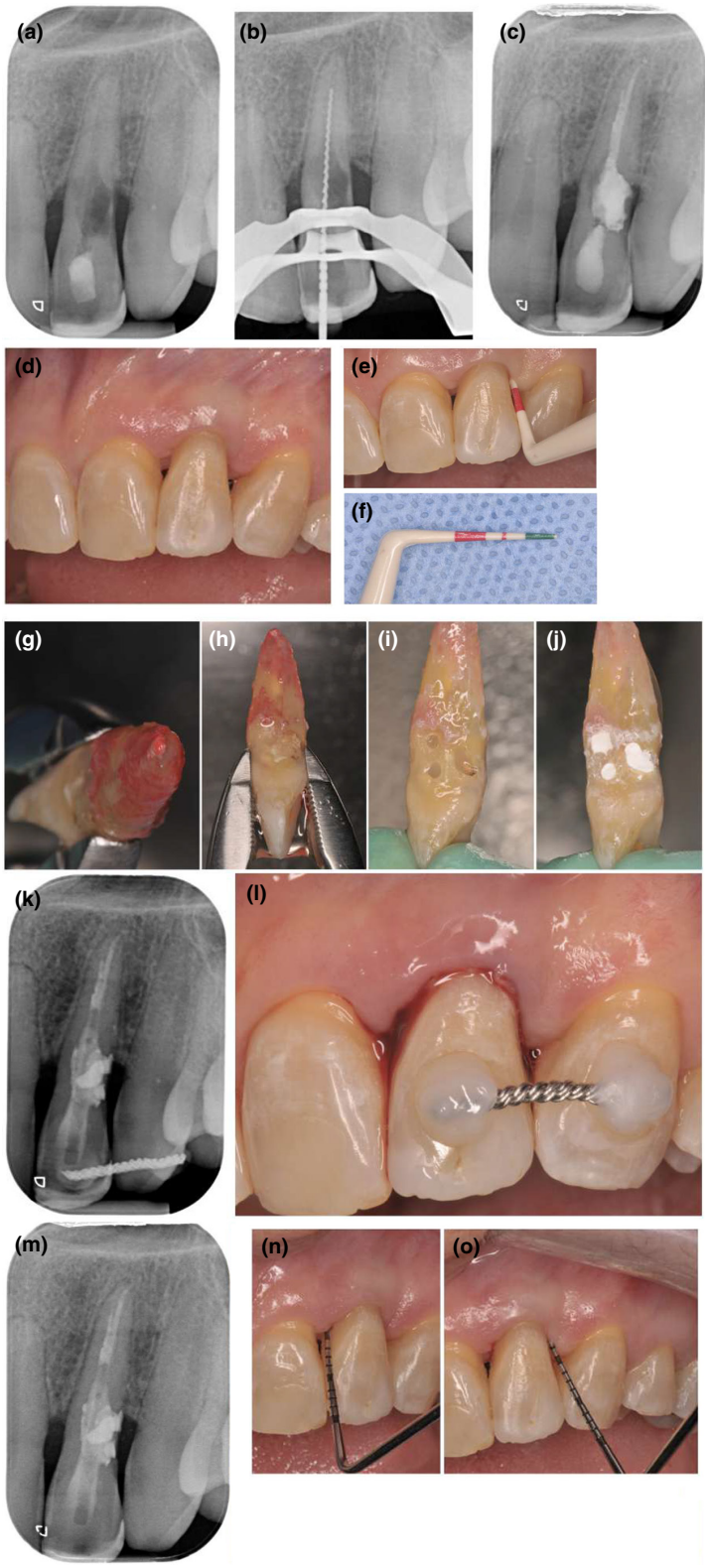

FIGURE 3 (a–f) Treatment attempt of an external cervical resorption was performed using an orthograde approach with chemo-mechanical preparation and bioceramic sealer filling. The radiographic aspect of the treatment was incomplete and after 3 weeks bleeding on probing was still present and the pocket depth was >5 mm; symptoms of dull pain were still present in the periodontal area. (g–l) Atraumatic extraction was performed and multiple sites of perforation were present on the root surface; they were cleaned with high-speed bur and sealed using bioceramic repair material. The tooth was replanted in site with conventional methods and splinted with a semirigid wire for 10 days. (m-o) Two months follow-up showing reduced pocket depth and bleeding on probing with no symptoms

rubber band on the forceps handle may help in securing this step (Kratchman, 1997). While performing extra-oral procedures a protection of the blood-filled socket with sterile gauzes could be used to reduce the contamination in the site (Cho et al., 2016). Before starting the extra-oral procedures on the extracted tooth, it is recommendable to have a visual inspection under microscope to find the presence of anatomical variations, accessory portals of exit or cracks (Choi et al., 2014; Jang et al., 2016a, 2016b; Kratchman, 1997; Niemczyk, 2001). In case, any doubts regarding the anatomical complexities can be cleared using methylene blue dye.

During the entire extra-oral procedures, the root surface must be wet, using sterile saline solution or Hank's balanced salt solution (HBSS) (Niemczyk, 2001). The total extra-oral time of manipulation is an important parameter for the long-term prognosis of the treatment, to avoid damaging the PDL and reduce the incidence of root resorption and ankylosis (Hupp et al., 1998). Lower survival rates were observed when the extra-oral time was more than 15 min (Jang et al., 2016a, 2016b).

Intentional replantation procedure can be performed to save the teeth with failed non-surgical root canal treatment. The procedure involves extra-oral retrograde filling of the root canal. In this procedure, apical one third (2–3 mm) of the root should be resected. The extra-oral orthograde root canal treatment improves the technical quality of the root canal filling. However, this procedure is recommended for highly selected cases since it can extend the extra-oral time and expose the root surface to the chemical risk due to the usage of irrigating solution.

After the apical root resection, a root-end preparation should be performed to ensure tight apical seal (Jang et al., 2016b). The root-end preparation is performed using a thin (0.5 mm tip) cylindrical, cut ended, diamond-coated or carbide high-speed bur (Deeb, 1971; Fegan & Steiman, 1991). The use of sonic or ultrasonic tips are also recommended, if the root is extremely thin (Cho et al., 2016). A retro cavity preparation should be performed under copious irrigation with sterile saline and extended to a depth of 3 mm (Becker, 2018).

Several retro-filling materials have been used such as amalgam, gutta-percha, zinc-oxide based materials and Mineral Trioxide Aggregate (Choi et al., 2014). Modern calcium silicate-based materials with different consistency and physical properties could be considered to be the materials of choice (Giacomino et al., 2019; Leal et al., 2013). The radiopacity and the setting time of the material should be considered as relevant factors while selecting the material (Khalil et al., 2016). Socket curettage is not recommended by several authors (Asgary et al., 2014; Cho et al., 2016; Kratchman, 1997). However, curettage can be performed gently when a periapical granuloma or extruded filling materials need to be removed. Once blood clot is removed, the tooth should be reinserted in the socket with digital pressure and the occlusion carefully checked (Becker, 2018). The replanted tooth should be immobilized using a flexible splint for a minimum period of 2 weeks. Alternatively, in posterior teeth, a crossed suture may be suspended above the occlusal surface with or without the use of resin composite to fix the suture to the tooth surface. The occlusion has to be relieved from occlusal contacts (Asgary et al., 2014; Becker, 2018; Choi et al., 2014; Jang et al., 2016b).

When the root canal treatment has not been performed before replantation, as described above, it is crucial to initiate orthograde endodontic treatment within 14 days from the replantation; even when apicoectomy and retrograde filling are performed extra-orally, an early root canal treatment after the surgical procedures increased the success rate of the intentionally replanted teeth (Chung et al., 2014). Necrotic pulp tissue inside the replanted tooth may induce a periapical lesion of endodontic origin or an infection-related root resorption (Bae et al., 2010; Tsukiboshi, 2002).

Intentional replantation also offers a suitable treatment option for teeth with inaccessible cervical resorptions. During this procedure, the granulation tissue within the defect is curetted to avoid recurrence. Depending on where the resorption is located in relation to the alveolar crest, glass-ionomer cements, composites or fast setting calcium silicate-based materials are the materials of choice to restore the cavity (European Society of Endodontology developed et al., 2018).

Teeth with vertical root fractures are traditionally deemed non-treatable. However, intentional replantation with extra-oral fragment bonding using a 4-methacryloxyethyl trimellitate anhydride/methacrylate-tri-n-butyl borane (4-META/ MMA-TBB) resin cement has been recommended to manage and maintain such teeth (Rosen et al., 2018). Two case series presented promising short term but unfavourable long-term data (Hayashi et al., 2002, 2004; Nizam et al., 2016). Thus, the treatment of teeth with vertical root fractures must still be regarded as unfeasible.

Tooth autotransplantation (Figures 4 and 5)

Despite the lack of evidence, the clinician should consider prescribing oral systemic antibiotics a few hours before the procedure to prevent bacterial infection from extra-oral and intra-oral sources. In children where the transplants are usually placed under general anaesthesia, a single dose of an antibiotic adjusted according to the weight of the child, can be administered intravenous by the anaesthetist after induction of general anaesthesia.

Teeth should be cleaned before surgery and surgical sites must be disinfected. The donor tooth and the recipient site have to be anaesthetized at same time. In donor tooth with immature root, revascularization can be expected after transplantation, hence local anaesthetic solution without vasoconstrictor should be preferred.

During the extraction of the tooth to be replaced, the dentist must be careful not to damage either the buccal or the lingual/palatal cortical plate surrounding the tooth. Extraction is relatively free from risk of root fractures,

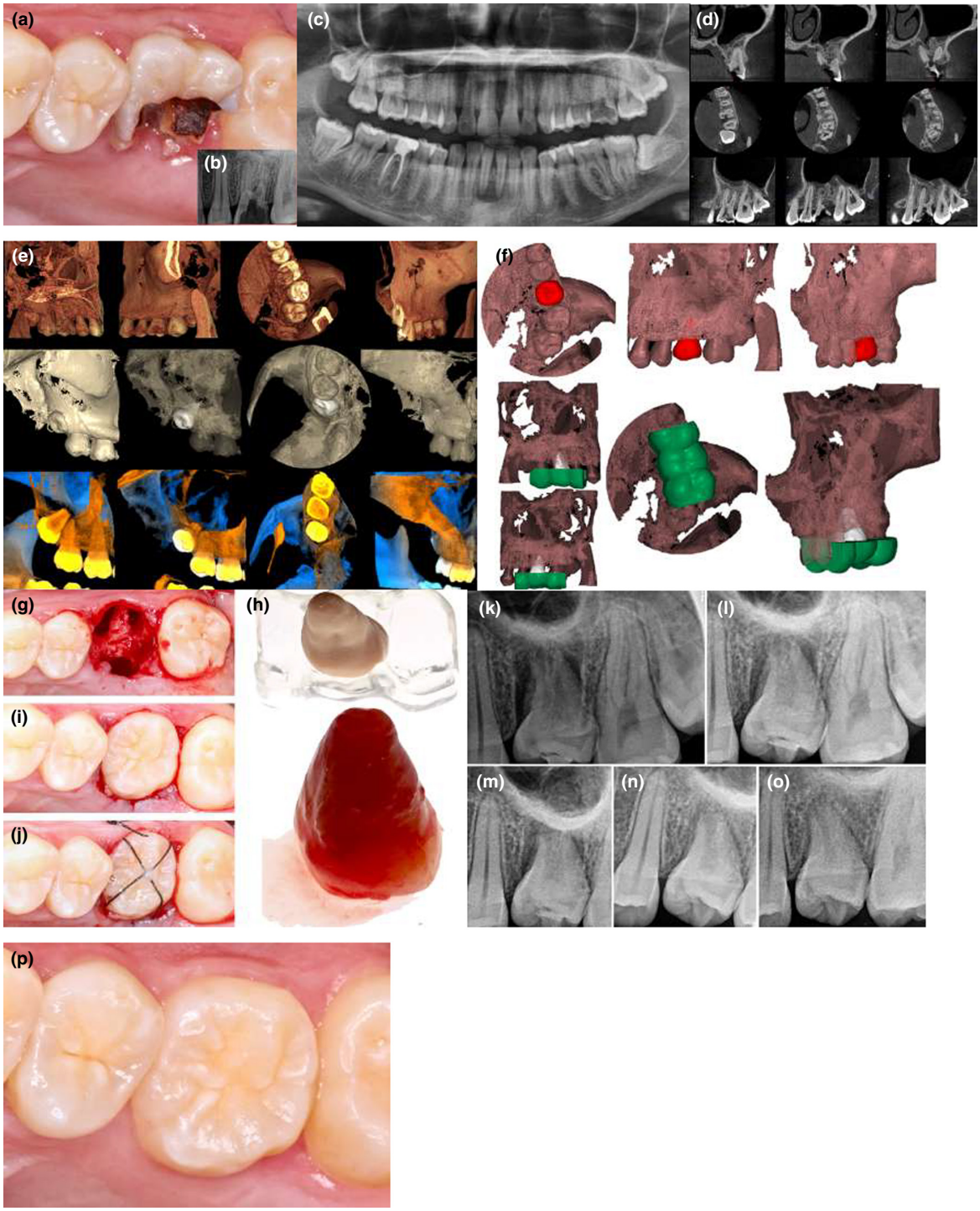

FIGURE 4 Autotransplantation of an immature third molar. (a) Occlusal view of unrestorable maxillary left first molar of a 26-year-old female. (b) Radiograph view showing extensive breakdown of affected tooth. (c) Panoramic radiograph. Transplantation of the maxillary right third molar was planned. (d) A limited cone-beam computed tomography (CBCT) scan (CS 8100; Carestream Health, Inc.) was made of the affected site and the donor tooth, showing the bone conditions of the recipient socket. (e) Medicine Digital Imaging and Communications in (DICOM) files from the 3-dimensional radiologic examination were uploaded into surgical planning software (Blue Sky Plan 3; Blue Sky Bio, LLC); the crown and root of the maxillary right third molar were segmented virtually. (f) Planning the 3-dimensional autotransplant positioning. (g) Atraumatic extraction of both the affected tooth and the donor tooth (h); to note the precision of the 3-dimensional tooth replica and the 3-dimensional-printed guiding template. (i) Immediate transplantation into the recipient socket. (j) Suture splinting to ensure adequate primary stability. (k) Periapical radiograph showing the final position of the donor tooth within the recipient socket. (l-o) Radiographic controls at 2, 6, 12 and 24 months showing continued root development and partial pulp canal obliteration. (p) Clinical view at 2 years follow-up: the crown and surrounding gingiva looked normal and the tooth responded positively to the pulp vitality test

FIGURE 5 Autotransplantation of a mature third molar. Pre-operative radiograph (a) and clinical (b) view of an unrestorable mandibular right second molar in a 40-year-old male. (c) The donor tooth (mandibular right third molar) immediately after extraction. (d) Preparation of the recipient site after extraction of the second molar. (e) Clinical view immediately after transplantation of the donor tooth. (f–g) Periapical radiographs showing the final position of the donor tooth and the splint to the adjacent tooth with wire and composite resin after etching and bonding. (h) Periapical radiographs showing the endodontic treatment 4 weeks after transplantation. (i) Overlay cavity preparation with complete cuspid coverage. (j) Monolithic painted lithium disilicate overlay after adhesive cementation. Radiographic (k) and clinical (l) follow-up at 3 months. (m) Radiographic view at 3 years follow-up showing a normal periodontal ligament space and lamina dura

especially in children, who have immature teeth with incomplete roots. Therefore, placement of sterile gauge on the donor tooth to be extracted, under the beaks of the extraction forceps, can minimize injury to the gingival fibres around the neck of the tooth.

In some cases, there are patients with certain conditions such as congenitally missing teeth or with early tooth loss, in which the recipient site for autotransplantation needs to be created surgically (Yu et al., 2017). With modern instrumentation used for placement of implants this is relatively an easy procedure. Anssari Moin et al. (2017) described a method of computer-assisted template-guided autotransplantation with custom 3D designed/printed surgical tooling that may possibly offer an alternative and more precise method for socket preparation.

To make sure that the donor tooth is not inserted with undue pressure, the recipient site should be larger according than the 3D dimensions of the tooth replica. The tooth replica is optimally positioned in the recipient site as digitally planned. The donor tooth should be extracted atraumatically and then compared to the tooth replica for shape and size. It is preferable to make an intra-crevicular incision before luxation to preserve as much PDL as possible. As soon as possible the donor tooth is placed in the recipient site in slight infraposition, leaving it free from occlusal and articulation forces.

In the case of sufficient transplant stability, postoperative fixation is carried out with a suture crossing the occlusal surface, leaving the site left to heal for 7 days. In case of inadequate stability and in children and adolescents, a buccal composite and flexible wire splint, to confirm the physiological mobility of the transplant, is applied for 4 weeks. Occlusal adjustment can be repeated after placing the splint. To achieve a tight fit around the donor tooth, it is recommended to trim the flap and suture it before placing the donor tooth in the socket. Some authors such as Tsukiboshi (2002) recommend the use of a surgical dressing to protect the transplant against infection during the first 2–3 days of healing, although the authors do not recommend this as it could prevent access to the area for effective plaque removal, thereby possibly compromising healing of the gingival fibres.

A radiograph might be taken before splinting to corroborate the position of the donor tooth in the recipient socket, although this is not usually required. Having observed that the position is adequate, the clinician will can place the splint if this is required.

After tooth transplantation, root apex closure and positive response to electric pulp tests are expected if the donor tooth had an immature root or an incomplete root development and revascularization is expected to occur. However, these might not be possible in the first few months after the procedure. In case of any signs or symptoms of pulp pathology like irreversible pulpitis or inflammatory root resorption, the clinician has to initiate the root canal treatment immediately.

In teeth with mature roots, if the donor is accessible, the root canal treatment can be completed before surgery. However, if the donor is impacted or erupted in a position that makes endodontic access difficult, non-surgical root canal treatment should be started before splint removal at 2 weeks post-surgery. The clinician can opt to complete the endodontic treatment in the same visit or place an interim dressing of calcium hydroxide in the root canal system. An alternative option is to perform the root canal treatment extra-orally at the time of transplantation; however, this is not recommended during the procedure because there is a clear risk of damage to PDL and extend the extra-oral time.

Once the splint is removed, the transplanted tooth should be allowed to settle naturally into its new position; however, it is adviceable to periodically check the occlusion. According to the aesthetics and function of the tooth, restorative treatment can be performed.

On many occasions, especially in growing patients, tooth autotransplantation may be part of a global orthodontic treatment. However, no studies have been carried out as to whether orthodontic forces affect the success and/or survival rate of the autotransplanted teeth (Rohof et al., 2018). As transplanted teeth are considered as any traumatized tooth with a PDL injury, any planned orthodontic movement of the transplanted teeth should be delayed for 6 months after surgery (Day et al., 2008; Kindelan et al., 2008).

The teeth should be re-evaluated as often as is done with the other teeth. It is important to inform the patient that the transplanted tooth is subject to the same risks as those of any other natural tooth.

FUTURE DIRECTIONS

Although the described methods, surgical extrusion, intentional replantation and autotransplantation, have been used clinically for decades, they share a limited level of evidence. For unrestorable teeth, intended for extrusion, comparative data addressing both orthodontic and surgical extrusion are highly desirable. So far only one animal study is available, which demonstrated that a functional periodontal ligament was restored irrespective of the extrusion modality (Kim et al., 2009). However, comparative clinical studies are needed to generate evidence on which approach is more likely to maximize both the long-term survival and the aesthetic outcome of the affected teeth.

In general, clinical studies must focus more on the study design with adequate sample size, long-term follow-ups and possible factors influencing the outcome of these procedures. Multi-centre clinical studies can help the researchers to achieve higher sample sizes, an important drawback in many studies is a small sample. Studies on quality of life and cost effectiveness of these three procedures are also needed. The overall satisfaction should be compared to the assessment done by the professionals, as professionals may be more critical than patients regarding the assessment of the aesthetic aspects of autotransplanted teeth.

Future studies are required to investigate whether orthodontic forces affect the success or survival of extruded or replanted teeth as well as the role of CBCT planning and use of 3D tooth replicas. It should also be further verified if preapplication of orthodontic force may be beneficial for the extraction phase in all these procedures, as it may increases PDL width, which induces tooth mobility, helping atraumatic extraction and PDL healing (Choi et al., 2014; Suzaki et al., 2008).

If the tooth autotransplantation or replantation cannot be undertaken immediately after the extraction of the recipient tooth, due to severe damage to the alveolar bone or to a previously extracted donor tooth, the cryopreservation systems could possibly be used to store donor teeth for a long period (Kaku et al., 2015). Teeth extracted due to orthodontic reasons or impacted third molars are most suitable for cryopreservation and future transplantation (Osathanon, 2010). Mechanical properties like cracks of cryopreserved tooth are important after autotransplantation, for which randomized clinical studies are needed to obtain more evidence on masticatory function and periodontal healing of transplanted cryopreserved teeth (Kaku et al., 2010).

The use of growth factors provided by platelet-rich plasma might have helped to maintain the vitality of the transplanted teeth, promote root formation and neurosensory development. Researchers are encouraged to conduct multi-centre randomized clinical studies to investigate the role of such different types of plasma and/or growth factors.

During tooth autotransplantation, the recipient socket must have enough alveolar supporting buccal and palatal/lingual plates to accommodate the donor tooth and the clinician must ensure that the flap in the cervical area is tightly repositioned (Imazato & Fukunishi, 2004). Post-transplantation, studies have shown rapid bone regeneration and the emergence of lamina dura, such that bone graft materials are unnecessary between bone walls and transplant roots even in a wide space (Inoue et al., 1988, Inoue et al., 1990). However, cases have been recorded in which the width of the root of the transplanted tooth is greater than the width of the recipient site, leading to root protrusion though bone dehiscence. In these situations, clinicians can place graft materials over the exposed root to promote bone regeneration, or they can rotate or resect one or more roots to fit into the socket (Yu et al., 2017). Guided tissue regeneration (GTR) or autogenous bone graft effects appears to be based on maintaining space for osteoblastic cells by excluding contact between gingival connective tissue and PDL (Imazato & Fukunishi, 2004). In patients with inadequate bone support, outcome of transplantation of teeth including GBR or GTR procedures or transplantation of teeth with cortical bone plates attached should be investigated (Zufía et al., 2017).

Because revascularization rates of mature teeth are significantly low, endodontic treatment is the standard procedure to avoid pulpal necrosis with subsequent periapical inflammation and inflammatory root resorption (Bae et al., 2010; Lundberg & Isaksson, 1996; Schwartz et al., 1985; Tsukiboshi, 2002). However, some studies (Skoglund & Tronstad, 1981; Skoglund et al., 1978) and published clinical cases (Gaviño Orduña et al., 2020; Jakse et al., 2018) have demonstrated that an extra-oral apicoectomy could enlarge the foramen of the transplant and achieve higher rates of revascularization. The critical diameter of the apical foramen of the transplanted tooth is considered to be 1 mm for successful revascularization (Andreasen et al., 1990). Raabe et al. (2021) concluded that extra-oral root-end resection of mature transplants may lead to higher rates of revascularization and post-operative pulp canal obliteration than those reported on unmodified mature transplants. However, prospective controlled clinical studies on extra-oral apicoectomy are needed to corroborate these results, and currently this is not a recommended clinical practice due to the risk of damage to the PDL while performing such procedures.

CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this manuscript.

AUTHOR CONTRIBUTIONS

All the authors have made substantial contributions to the manuscript. All the authors of this manuscript have read and approved the final version of the manuscript.

ETHICAL STATEMENT

Ethical approval was not acquired as this article does not contain research that involved any human or animal experiments.

ORCID

Gianluca Plotino https://orcid.org/0000-0003-3003-8029
Francesc Abella Sans https://orcid.org/0000-0002-3500-3039
Monty S. Duggal https://orcid.org/0000-0003-3652-5741
Nicola M. Grande https://orcid.org/0000-0003-3407-9768
Gabriel Krastl https://orcid.org/0000-0002-9402-8121
Venkateshbabu Nagendrababu https://orcid.org/0000-0003-3783-3156

REFERENCES

Akhlef, Y., Schwartz, O., Andreasen, J.O. & Jensen, S.S. (2018) Autotransplantation of teeth to the anterior maxilla: a systematic review of survival and success, aesthetic presentation and patient-reported outcome. *Dental Traumatology*, 34, 20–27.

Almpani, K., Papageorgiou, S.N. & Papadopoulos, M.A. (2015) Autotransplantation of teeth in humans: a systematic review and meta-analysis. *Clinical Oral Investigation*, 19, 1157–1179.

Andersson, L., Bodin, I. & Sorensen, S. (1989) Progression of root resorption following replantation of human teeth after extended extraoral storage. *Endodontics and Dental Traumatology*, 5, 38–47.

Andreasen, J.O. (1981) The effect of pulp extirpation or root canal treatment on periodontal healing after replantation of permanent incisors in monkeys. *Journal of Endodontics*, 7, 245–252.

Andreasen, J.O., Borum, M.K., Jacobsen, H.L. & Andreasen, F.M. (1995) Replantation of 400 avulsed permanent incisors. 4. Factors related to periodontal ligament healing. *Endodontics & Dental Traumatology*, 11, 76–89.

Andreasen, J.O., Paulsen, H.U., Yu, Z., Ahlquist, R., Bayer, T. & Schwartz, O. (1990) A long-term study of 370 autotransplanted premolars. Part I. Surgical procedures and standardized techniques for monitoring healing. *European Journal of Orthodontics*, 12, 3–13.

Angerame, D., De Biasi, M., Kalaj, B. & Maglione, M. (2021) Surgical extrusion: a dental technique. *Journal of Prosthetic Dentistry*, 125, 23–28.

Anssari Moin, D., Verweij, J.P., Waars, H., van Merkesteyn, R. & Wismeijer, D. (2017) Accuracy of computed-assisted template guided autotransplantation of teeth with custom three-dimensional designed/printed surgical tooling: a cadaveric study. *Journal of Oral and Maxillofacial Surgery*, 75, e1–e7.

Asgary, S., Alim Marvasti, L. & Kolahdouzan, A. (2014) Indications and case series of intentional replantation of teeth. *Iranian Endodontic Journal*, 9, 71–78.

Asgary, S. & Roghanizadeh, L. (2018) Rapid bone healing after intentional replantation of a molar with apical actinomycosis. *Iranian Endodontic Journal*, 13(1), 135.

Atala-Acevedo, C., Abarca, J., Martínez-Zapata, M.J., Díaz, J., Olate, S. & Zaror, C. (2017) Success rate of autotransplantation of teeth with an open apex: systematic review and meta-analysis. *Journal of Oral and Maxillofacial Surgery*, 75, 35–50.

Bae, J.H., Choi, Y.H., Cho, B.H., Kim, Y.G. & Kim, S.G. (2010) Autotransplantation of teeth with complete root formation: a case series. *Journal of Endodontics*, 36, 1422–1426.

Becker, B.D. (2018) Intentional replantation techniques: a critical review. *Journal of Endodontics*, 44, 14–21.

Bender, I.B. & Rossman, L.E. (1993) Intentional replantation of endodontically treated teeth. *Oral Surgery, Oral Medicine, Oral Pathology*, 76, 623–630.

Borring-Møller, G. & Frandsen, A. (1978) Autologous tooth transplantation to replace molars lost in patients with juvenile periodontitis. *Journal of Clinical Periodontology*, 5, 152–158.

Caliskan, M.K., Turkun M. & Gomel, M. (1999) Surgical extrusion of crown-root-fractured teeth: A clinical review. *International Endodontic Journal*, 32, 146-151.

Chércoles-Ruiz, A., Sánchez-Torres, A. & Gay-Escoda, C. (2017) Endodontics, endodontic retreatment and apical surgery versus tooth extraction and implant placement: a systematic review. *Journal of Endodontics*, 43, 679–686.

Cho, S.Y., Lee, Y., Shin, S.J., Kim, E., Jung, I.Y., Friedman, S. et al. (2016) Retention and healing outcomes after intentional replantation. *Journal of Endodontics*, 42, 909–915.

Choi, Y.H., Bae, J.H., Kim, Y.K., Kim, H.Y., Kim, S.K. & Cho, B.H. (2014) Clinical outcome of intentional replantation with preoperative orthodontic extrusion: a retrospective study. *International Endodontic Journal*, 47, 1168–1176.

Choi, Y.H. & Lee, H.J. (2019) Surgical extrusion of a maxillary premolar after orthodontic extrusion: a retrospective study. *Journal of the Korean Association of Oral and Maxillofacial Surgeons*, 45, 254–259.

Chung, W.C., Tu, Y.K., Lin, Y.H. & Lu, H.K. (2014) Outcomes of autotransplanted teeth with complete root formation: a systematic review and meta-analysis. *Journal of Clinical Periodontology*, 41, 412–423.

Conklin, W.W. (1974) Transplantation of third molar into edentulous site. *Oral Surgery, Oral Medicine, Oral Pathology*, 38, 193–197.

Czochrowska, E.M., Stenvik, A., Bjercke, B. & Zachrisson, B.U. (2002) Outcome of tooth transplantation: survival and success rates 17–41 years posttreatment. *American Journal of Orthodontics and Dentofacial Orthopedics*, 121, 110–119.

Das, B. & Muthu, M.S. (2013) Surgical extrusion as a treatment option for crown-root fracture in permanent anterior teeth: a systematic review. *Dental Traumatology*, 29, 423–431.

Day, P.F., Kindelan, S.A., Spencer, J.R., Kindelan, J.D. & Duggal, M.S. (2008) Dental trauma: part 2. Managing poor prognosis anterior teeth–treatment options for the subsequent space in a growing patient. *Journal of Orthodontics*, 35, 143–155.

Deeb, E. (1971) Replantation of teeth–a recommended procedure. *Journal of South California Dental Association*, 39, 24–29.

Dietrich, T., Krug, R., Krastl, G. & Tomson, P.L. (2019) Restoring the unrestorable! Developing coronal tooth tissue with a minimally invasive surgical extrusion technique. *British Dental Journal*, 226, 789–793.

Elkhadem, A., Mickan, S. & Richards, D. (2014) Adverse events of surgical extrusion in treatment for crown-root and cervical root fractures: a systematic review of case series/reports. *Dental Traumatology*, 30, 1–14.

European Society of Endodontology, Patel, S., Lambrechts, P., Shemesh, H. & Mavridou, A. (2018) European Society of Endodontology position statement: external cervical resorption. *International Endodontic Journal*, 51, 1323–1326.

Fegan, S. & Steiman, H.R. (1991) Intentional replantation. *Journal of Michigan Dental Association*, 73, 22–24.

Fouad, A.F., Abbott, P.V., Tsilingaridis, G., Cohenca, N., Lauridsen, E., Bourguignon, C. et al. (2020) International Association of Dental Traumatology guidelines for the management of traumatic dental injuries: 2. Avulsion of permanent teeth. *Dental Traumatology*, 36(4), 331–242.

de Freitas Coutinho, N.B., Nunes, F.C., Gagno Intra, J.B., Roldi, A., de Jesus-Soares, A., Coelho, M.S. et al. (2021) Success, survival rate, and soft tissue esthetic of tooth autotransplantation. *Journal of Endodontics*, 47, 391–396.

Garrido, I., Abella, F., Ordinola-Zapata, R., Duran-Sindreu, F. & Roig, M. (2016) Combined endodontic therapy and intentional replantation for the treatment of palatogingival groove. *Journal of Endodontics*, 42, 324–328.

Gaviño Orduña, J.F., García García, M., Dominguez, P., Caviedes Bucheli, J., Martin Biedma, B., Abella Sans, F. et al. (2020) Successful pulp revascularization of an autotransplantated mature premolar with fragile fracture apicoectomy and plasma rich in growth factors: a 3-year follow-up. *International Endodontic Journal*, 53, 421–433.

Giacomino, C.M., Wealleans, J.A., Kuhn, N. & Diogenes, A. (2019) Comparative biocompatibility and osteogenic potential of two bioceramic sealers. *Journal of Endodontics*, 45, 51–56.

Gilijamse, M., Baart, J.A., Wolff, J., Sándor, G.K. & Forouzanfar, T. (2016) Tooth autotransplantation in the anterior maxilla and mandible: retrospective results in young patients. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 122, e187–e192.

Grossman, L.I. (1966) Intentional replantation of teeth. *The Journal of the American Dental Association*, 72, 1111–1118.

Grzanich, D., Rizzo, G. & Silva, R.M. (2017) Saving natural teeth: intentional replantation-protocol and case series. *Journal of Endodontics*, 43, 2119–2124.

Hayashi, M., Kinomoto, Y., Miura, M., Sato, I., Takeshige, F. & Ebisu, S. (2002) Short-term evaluation of intentional replantation of vertically fractured roots reconstructed with dentin-bonded resin. *Journal of Endodontics*, 28, 120–124.

Hayashi, M., Kinomoto, Y., Takeshige, F. & Ebisu, S. (2004) Prognosis of intentional replantation of vertically fractured roots reconstructed with dentin-bonded resin. *Journal of Endodontics*, 30, 145–148.

Hernandez, S.L. & Cuestas-Carnero, R. (1988) Autogenic tooth transplantation: a report of ten cases. *Journal of Oral and Maxillofacial Surgery*, 46, 1051–1055.

Hong, B., Bulsara, Y., Gorecki, P. & Dietrich, T. (2018) Minimally invasive vertical versus conventional tooth extraction: an interrupted time series study. *Journal of the American Dental Association*, 149, 688–695.

Hou, G.L., Hou, L.T. & Weisgold, A. (2016) Survival rate of teeth with periodontally hopeless prognosis after therapies with intentional replantation and perioprosthetic procedures - a study of case series for 5–12 years. *Clinical Experimetal Dental Research*, 2, 85–95.

Hupp, J.G., Mesaros, S.V., Aukhil, I. & Trope, M. (1998) Periodontal ligament vitality and histologic healing of teeth stored for extended periods before transplantation. *Endodontics and Dental Traumatology*, 14, 79–83.

Imazato, S. & Fukunishi, K. (2004) Potential efficacy of GTR and autogenous bone graft for autotransplantation to recipient sites with osseous defects: evaluation by re-entry procedure. *Dental Traumatology*, 20, 42–47.

Jakse, N., Ruckenstuhl, M., Rugani, P., Kirnbauer, B., Sokolowski, A. & Ebeleseder, K. (2018) Influence of extraoral apicoectomy on revascularization of an autotransplanted tooth: a case report. *Journal of Endodontics*, 44, 1298–1302.

Jang, Y., Choi, Y.J., Lee, S.J., Roh, B.D., Park, S.H. & Kim, E. (2016a) Prognostic factors for clinical outcomes in autotransplantation of teeth with complete root formation: survival analysis for up to 12 years. *Journal of Endodontics*, 42, 198–205.

Jang, Y., Lee, S.J., Yoon, T.C., Roh, B.D. & Kim, E. (2016b) Survival rate of teeth with a C-shaped canal after intentional replantation: *a s*tudy of 41 cases for up to 11 years. *Journal of Endodontics*, 42, 1320–1325.

Jonsson, T. & Sigurdsson, T.J. (2004) Autotransplantation of premolars to premolar sites. A long-term follow-up study of 40 consecutive patients. *American Journal of Orthodontics and Dentofacial Orthopedic*, 125, 668–675.

Kafourou, V., Tong, H.J., Day, P., Houghton, N., Spencer, R.J. & Duggal, M. (2017) Outcomes and prognostic factors that influence the success of tooth autotransplantation in children and adolescents. *Dental Traumatology*, 33, 393–399.

Kahler, B., Hu, J.Y., Marriot-Smith, C.S. & Heithersay, G.S. (2016) Splinting of teeth following trauma: a review and a new splinting recommendation. *Australian Dental Journal*, 61(Suppl 1), 59–73.

Kahnberg, K.E. (1985) Intraalveolar transplantation of teeth with crown-root fractures. *Journal of Oral and Maxillofacial Surgery*, 43, 38–42.

Kahnberg, K.E. (1988) Surgical extrusion of root-fractured teeth–a follow-up study of two surgical methods. *Endodontics & Dental Traumatology*, 4, 85–89.

Kahnberg, K.E. (1996) Intra-alveolar transplantation. I. A 10-year follow-up of a method for surgical extrusion of root fractured teeth. *Swedish Dental Journal*, 20, 165–172.

Kahnberg, K.E., Warfvinge, J. & Birgersson, B. (1982) Intraalveolar transplantation. (I). The use of autologous bone transplants in the periapical region. *International Journal of Oral Surgery*, 11, 372–379.

Kaku, M., Kamada, H., Kawata, T., Koseki, H., Abedini, S., Kojima, S. et al. (2010) Cryopreservation of periodontal ligament cells with magnetic field for tooth banking. *Cryobiology*, 61, 73–78.

Kaku, M., Shimasue, H., Ohtani, J., Kojima, S., Sumi, H., Shikata, H. et al. (2015) A case of tooth autotransplantation after long-term cryopreservation using a programmed freezer with a magnetic field. *The Angle Orthodontist*, 85, 518–524.

Kelly, R.D., Addison, O., Tomson, P.L., Krastl, G. & Dietrich, T. (2016) Atraumatic surgical extrusion to improve tooth restorability: a clinical report. *Journal of Prosthetics Dentistry*, 115, 649–653.

Khalil, I., Naaman, A. & Camilleri, J. (2016) Properties of tricalcium silicate sealers. *Journal of Endodontics*, 42, 1529–1535.

Kim, S.H., Tramontina, V.A., Ramos, C.M., Prado, A.M., Passanezi, E. & Greghi, S.L. (2009) Experimental surgical and orthodontic extrusion of teeth in dogs. *International Journal of Periodontics Restorative Dentistry*, 29, 435–443.

Kindelan, S.A., Day, P.F., Kindelan, J.D., Spencer, J.R. & Duggal, M.S. (2008) Dental trauma: an overview of its influence on the management of orthodontic treatment. Part 1. *Journal of Orthodontics*, 35, 68–78.

Krastl, G., Filippi, A., Zitzmann, N.U., Walter, C. & Weiger, R. (2011) Current aspects of restoring traumatically fractured teeth. *The European Journal of Esthetic Dentistry*, 6, 124–141.

Krastl, G., Weiger, R., Filippi, A., Van Waes, H., Ebeleseder, K., Ree, M. et al. (2021a) Endodontic management of traumatized permanent teeth: a comprehensive review. *International Endodontic Journal*, 54, 1221–1245.

Krastl, G., Weiger, R., Filippi, A., Van Waes, H., Ebeleseder, K., Ree, M. et al. (2021b) European Society of Endodontology position statement: endodontic management of traumatized permanent teeth. *International Endodontic Journal*, 54, 1473–1481.

Kratchman, S. (1997) Intentional replantation. *Dental Clinics of North America*, 41, 603–617.

Kristerson, L. (1985) Auto transplantation of human premolars. A clinical and radiographic study of 100 teeth. *International Journal of Oral Surgery*, 14, 200–213.

Kristerson, L. & Lagerström, L. (1991) Autotransplantation of teeth in cases with agenesis or traumatic loss of maxillary incisors. *European Journal of Orthodontics*, 123, 486–492.

Krug, R., Connert, T., Soliman, S., Syfrig, B., Dietrich, T. & Krastl, G. (2018a) Surgical extrusion with an atraumatic extraction system: a clinical study. *Journal of Prosthetic Dentistry*, 120, 879–885.

Krug, R., Kremeier, K. & Krastl, G. (2018b) Long-term retention of avulsed maxillary permanent incisors replanted after prolonged non-physiological storage. *Dental Traumatology*, 35, 147–152.

Krug, R., Soliman, S. & Krastl, G. (2019) Intentional replantation with an atraumatic extraction system in teeth with extensive cervical resorption. *Journal of Endodontics*, 45, 1390–1396.

Kugelberg, R., Tegsjö, U. & Malmgren, O. (1994) Autotransplantation of 45 teeth to the upper incisor region in adolescents. *Swedish Dental Journal*, 18, 165–172.

Kumar, R., Khambete, N. & Priya, E. (2013) Successful immediate autotransplantation of tooth with incomplete root formation: case report. *Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology*, 115, e16–e21.

Leal, F., De-Deus, G., Brandao, C., Luna, A., Souza, E. & Fidel, S. (2013) Similar sealability between bioceramic putty ready-to-use repair cement and white MTA. *Brazilian Dental Journal*, 24, 362–366.

Lee, S.J., Jung, I.Y., Lee, C.Y., Choi, S.Y. & Kum, K.Y. (2001) Clinical application of computer-aided rapid prototyping for tooth transplantation. *Dental Traumatology*, 17, 114–119.

Lee, S.J. & Kim, E. (2012) Minimizing the extra-oral time in autogeneous tooth transplantation: use of computer-aided rapid prototyping (CARP) as a duplicate model tooth. *Restorative Dentistry and Endodontics*, 37, 136–141.

Llaquet Pujol, M., Pascual La Rocca, A., Casaponsa Parerols, J. & Abella Sans, F. (2021) Biologically oriented preparation technique for surgically extruded teeth: a clinical report. *Journal of Prosthetics Dentistry*, 126, 2–7.

Lundberg, T. & Isaksson, S. (1996) A clinical follow-up study of 278 autotransplanted teeth. *British Journal of Oral and Maxillofacial Surgery*, 34, 181–185.

Mainkar, A. (2017) A systematic review of the survival of teeth intentionally replanted with a modern technique and cost-effectiveness compared with single-tooth implants. *Journal of Endodontics*, 43, 1963–1968.

Mejàre, B., Wannfors, K. & Jansson, L. (2004) A prospective study on transplantation of third molars with complete root formation. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology*, 97, 231–238.

Mohamed, M., Moheb, D., Waly, N., Abdalsamad, A. & Elkhadem, A. (2021) Effects of different splinting times on surgically extruded teeth with a crown-root fracture: a randomized controlled trial. *Dental Traumatology*, 37, 264–274.

Muska, E., Walter, C., Knight, A., Taneja, P., Bulsara, Y., Hahn, M. et al. (2013) Atraumatic vertical tooth extraction: a proof of principle clinical study of a novel system. *Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology*, 116, e303–e310.

Natiella, J.R., Armitage, J.E. & Greene, G.W. (1970) The replantation and transplantation of teeth. A review. *Surgery, Oral Medicine, Oral Pathology*, 29, 397–419.

Niemczyk, S.P. (2001) Re-inventing intentional replantation: a modification of the technique. *Practical Procedures Aesthetic Dentistry*, 13, 433–439.

Nizam, N., Kaval, M.E., Gurlek, O., Atila, A. & Caliskan, M.K. (2016) Intentional replantation of adhesively reattached vertically fractured maxillary single-rooted teeth. *International Endodontic Journal*, 49, 227–236.

Oh, S., Kim, S., Lo, H.S., Choi, J.Y., Kim, H.J., Ryu, G.J. et al. (2018) Virtual simulation of autotransplantation using 3-dimensional printing prototyping model and computer-assisted design program. *Journal of Endodontics*, 44, 1883–1888.

Oikarinen, K.S., Stoltze, K. & Andreasen, J.O. (1996) Influence of conventional forceps extraction and extraction with an extrusion instrument on cementoblast loss and external root resorption of replanted monkey incisors. *Journal of Periodontal Research*, 31, 337–344.

Okaguchi, M., Kuo, T. & Ho, Y.C. (2018) Successful treatment of vertical root fracture through intentional replantation and root fragment bonding with 4-meta/mma-tbb resin. *Journal of the Formosan Medical Association*, 118, 671–678.

Osathanon, T. (2010) Transplantation of cryopreserved teeth: a systematic review. *International Journal of Oral Science*, 2, 59–65.

Park, J.H., Tai, K. & Hayashi, D. (2010) Tooth autotransplantation as a treatment option: a review. *Journal of Clinical Pediatric Dentistry*, 35, 129–135.

Patil, S., Dumsha, T.C. & Sykdiskis, R.J. (1994) Determining periodontal ligament (PDL) cell vitality from exarticulated teeth stored in saline or milk using fluorescein diacetate. *International Endodontic Journal*, 27, 1–5.

Penny, R.E. & Kraal, J.H. (1979) Crown-to-root ratio: its significance in restorative dentistry. *Journal of Prosthetics Dentistry*, 42, 34–38.

Plakwicz, P., Wojtowicz, A. & Czochrowska, E.M. (2013) Survival and success rates of autotransplanted premolars: a prospective study of the protocol for developing teeth. *American Journal of Orthodontics and Dentofacial Orthopedics*, 144, 229–237.

Plotino, G., Abella Sans, F., Duggal, M.S., Grande, N.M., Krastl, G., Nagendrababu, V. et al. (2020) Clinical procedures and outcome of surgical extrusion, intentional replantation and tooth autotransplantation – a narrative review. *International Endodontic Journal*, 53, 1636–1652.

Raabe, C., Bornstein, M.M., Ducommun, J., Sendi, P., von Arx, T. & Janner, S.F.M. (2021) A retrospective analysis of autotransplanted teeth including an evaluation of a novel surgical technique. *Clinical Oral Investigation*, 25, 3513–3525.

Rohof, E.C.M., Kerdijk, W., Jansma, J., Livas, C. & Ren, Y. (2018) Autotransplantation of teeth with incomplete root formation: a

systematic review and meta-analysis. *Clinical Oral Investigation*, 22, 1613–1624.

Rosen, E., Beitlitum, I. & Tsesis, I. (2018) The preservation of teeth with root-originated fractures. *Evidence-Based Endodontics*, 3, 2–8.

Saida, H., Fukuba, S., Miron, R. & Shirakata, Y. (2018) Efficacy of flapless intentional replantation with enamel matrix derivative in the treatment of hopeless teeth associated with endodontic-periodontal lesions: a 2-year prospective case series. *Quintessence International*, 49, 699–707.

Saund, D. & Dietrich, T. (2013) Minimally-invasive tooth extraction: doorknobs and strings revisited! *Dental Update*, 40(4), 325–330, 8–30.

Schatz, J.P. & Joho, J.P. (1992) Long-term clinical and radiologic evaluation of autotransplanted teeth. *International Journal of Oral and Maxillofacial Surgery*, 21, 271–275.

Schwartz, O., Bergmann, P. & Klausen, B. (1985) Autotransplantation of human teeth. A life-table analysis of prognostic factors. *International Journal of Oral and Maxillofacial Surgery*, 14, 245–258.

Shahbazian, M., Jacobs, R., Wyatt, J., Willems, G., Pattijn, V., Dhoore, E. et al.(2010) Accuracy and surgical feasibility of a CBCT-based stereolithographic surgical guide aiding autotransplantation of teeth: in vitro validation. *Journal of Oral Rehabilitation*, 37, 854–859.

Skoglund, A., Tronstad, L. & Wallenius, K. (1978) A microangiographic study of vascular changes in replanted and autotransplanted teeth of young dogs. *Oral Surgery, Oral Medicine, Oral Pathology, and Oral Radiology*, 45, 17–28.

Skoglund, A. & Tronstad, L. (1981) Pulpal changes in replanted and autotransplanted immature teeth of dogs. *Journal of Endodontics*, 7, 309–316.

Slagsvold, O. & Bjercke, B. (1978) Applicability of autotransplantation in cases of missing upper anterior teeth. *American Journal of Orthodontics*, 74, 410–421.

Solakoglu, O. & Filippi, A. (2017) Transreplantation: an alternative for periodontally hopeless teeth. *Quintessence International*, 48, 287–293.

Strbac, G.D., Schnappauf, A., Giannis, K., Bertl, M.H., Moritz, A. & Ulm, C. (2016) Guided autotransplantation of teeth: a novel method using virtually planned 3- dimensional templates. *Journal of Endodontics*, 42, 1844–1850.

Strbac, G.D., Schnappauf, A., Bertl, M.H., Vasak, C., Ulm, C. & Giannis, K. (2020) Guided osteotomy and guided autotransplantation for treatment of severely impacted teeth: a proof-of-concept report. *Journal of Endodontics*, 46(11), 1791–1798.

Sugai, T., Yoshizawa, M., Kobayashi, T., Ono, K., Takagi, R., Kitamura, N. et al. (2010) Clinical study on prognostic factors for autotransplantation of teeth with complete root formation. *International Journal of Oral Maxillofacial Surgery*, 39, 1193–1203.

Sugaya, T., Tomita, M., Motoki, Y., Miyaji, H. & Kawamami, M. (2016) Influence of enamel matrix derivative on healing of root surfaces after bonding treatment and intentional replantation of vertically fractured roots. *Dental Traumatology*, 32, 397–401.

Suzaki, Y., Matsumoto, Y., Kanno, Z. & Soma, K. (2008) Preapplication of orthodontic forces to the donor teeth affects periodontal healing of transplanted teeth. *The Angle Orthodontist*, 78, 495–501.

Tegsjo, U., Valerius-Olsson, H. & Olgart, K. (1978) Intra-alveolar transplantation of teeth with cervical root fractures. *Swedish Dental Journal*, 2, 73–82.

Tegsjõ, U., Valerius-Olsson, H. & Olgart, K. (1978) Intra-alveolar transplantation of teeth with cervical root fractures. *Swedish Dental Journal*, 2, 73–82.

Tegsjo, U., Valerius-Olsson, H., Frykholm, A. & Olgart, K. (1987) Clinical evaluation of intra-alveolar transplantation of teeth with cervical root fractures. *Swedish Dental Journal*, 11, 235–250.

Torabinejad, M., Dinsbach, N.A., Turman, M., Handysides, R., Bahjri, K. & White, S.N. (2015) Survival of intentionally replanted teeth and implant-supported single crowns: a systematic review. *Journal of Endodontics*, 41, 992–998.

Tsukiboshi, M. (2002) Autotransplantation of teeth: requirements for predictable success. *Dental Traumatology*, 18, 157–180.

Verweij, J.P., Jongkees, F.A., Anssari Moin, D., Wismeijer, D. & van Merkesteyn, J.P.R. (2017) Autotransplantation of teeth using computer-aided rapid prototyping of a three-dimensional replica of the donor tooth: a systematic literature review. *International Journal of Oral Maxillofacial Surgery*, 46, 1466–1474.

Warfvinge, J. & Kahnberg, K.E. (1989) Intraalveolar transplantation of teeth. *Iv. Endodontic considerations. Swedish Dental Journal*, 13, 229–233.

Wu, S.Y. & Chen, G. (2021) A long-term treatment outcome of intentional replantation in Taiwanese population. *Journal of the Formosan Medical Association*, 120, 346–353.

Yu, H.J., Jia, P., Lv, Z. & Qiu, L.X. (2017) Autotransplantation of third molars with completely formed roots into surgically created sockets and fresh extraction sockets: a 10-year comparative study. *International Journal of Oral and Maxillofacial Surgery*, 46, 531–538.

Zufía, J., Abella, F., Trebol, I. & Gómez-Meda, R. (2017) Autotransplantation of mandibular third molar with buccal cortical plate to replace vertically fractured mandibular second molar: a novel technique. *Journal of Endodontics*, 43, 1574–1578.

How to cite this article: Plotino, G., Abella Sans, F., Duggal, M.S., Grande, N.M., Krastl, G., Nagendrababu, V. & et al. (2022) Present status and future directions: Surgical extrusion, intentional replantation and tooth autotransplantation. *International Endodontic Journal*, 55(Suppl. 3), 827–842. Available from: https://doi.org/10.1111/iej.13723