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Healing responses following transverse root fracture: a historical review and case reports showing healing with (a) calcified tissue and (b) dense fibrous connective tissue

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Abstract – *Background*: The understanding and management of transverse intra-alveolar root fractures has evolved to its current high level of sophistication and clinical success from foundations laid down by histological studies as early as the mid-nineteenth century. *Significance*: The aim of the review was to highlight those earlier histological reports and studies that have contributed to the current understanding of the biological processes involved in the healing of transverse root fractures. Healing of a transverse root fracture by calcified tissue was demonstrated histologically by Howe in 1926, while Boulger in 1928 showed the two other patterns of root fracture healing, namely the interposition of fibrous connective tissue and the interposition of bone and periodontal ligament around both fractured segments. Other major histological reports around that time came from members of the so-called 'The Vienna group of Illinois', who had a significant influence in the development of oral biology worldwide. Other important reports and an experimental study emanated from Germany and Switzerland in the late 30s and early 40s, followed in the 1950s and early 1960s by histological material principally from Sweden, Denmark, France, the USA and Britain. Jens Andreasen and Erik Hjörting-Hansen's landmark paper in 1967 included new histological reports and a classification of healing responses following transverse root fractures. The expansion of knowledge related to root fractures since that time has been exponential, with major contributions from Scandinavia and several other countries. *Case reports*: Accompanying the historical review are two case reports with histology of root fracture healing by (a) calcified tissue and (b) dense fibrous connective tissue. The role of the pulp and the periodontal ligament in the repair process is described and the clinical significance discussed with particular emphasis to diagnosis and orthodontic management.

Throughout the history of mankind, accidents, assaults, conflicts and wars have no doubt resulted in a wide range of dental injuries, including transverse root fractures. Although there was at least one report of a transverse root fracture, including histology in the mid-nineteenth century, it was not until the discovery of X-rays by the German physicist Wilhelm Roentgen in 1895, and the incorporation of this technology into dentistry, shortly thereafter by fellow countrymen Otto Walkoff and slightly later in the USA by C. Edmund Kells that the potential for the diagnosis of root fractures of teeth evolved. With improvements in X-ray equipment, images of teeth with root fractures became a clinical reality around 1920. Since that time there have been numerous case reports and some studies into the healing responses of transverse root fractures based on clinical and radiological evidence and these have been extensively reviewed (1–3). While such studies are extremely important, case reports or experimental studies with histology usually provide more detailed information regarding the biological responses of dental and supporting tissues to transverse tooth fractures. In 1955, the late Danish oral pathologist Professor Jens Pindborg tabulated a brief summary of 20 histological reports of transverse root fractures dating from 1904 to 1955 (4) and these and more recent reports have also been extensively reviewed (3).

This historical review was initiated to highlight those authors and their histological reports or studies dating from the mid-nineteenth century that seem to have contributed to the evolution of knowledge and understanding of the biological processes involved in the relatively uncommon dental injury of intra-alveolar transverse root fracture. Accompanying this review are two case reports with histology of root fracture healing by (a) calcified tissue and (b) dense fibrous connective tissue.

From early records, it is apparent that an appreciation of natural healing of root fractures was recognized as early as 1859 (5) by Sir John Tomes, a renowned English oral pathologist and 'Father of the British Dental Association'. He observed that 'when a tooth is fractured within a socket it may, under favourable circumstances, be reunited'. It would appear that the eminent nineteenth century Viennese Histologist/ Pathologist Professor Carl Wedl in 1869 was the first to publish histology of a tooth specimen demonstrating a transverse root fracture healed by hard tissue (6). At that time photomicroscopy had not been developed and histological specimens were meticulously recorded by laboratory artists, in this case by Dr C Heitzmann. The reparative hard tissue consisted of dentin, globular masses and bone. Wedl in a subsequent publication surmised from the histological material that repair originated primarily from the pulpal tissue and to a lesser extent the periodontium (7). Commenting on Wedl's 1869 publication, Sir John Tomes in 1873, now with his son Charles as co-author, stated 'The dentinal pulp may however take some share in uniting the fragment of tooth broken within the socket' (8).

In the 1920s with the advantage of photomicroscopy, a few more reports demonstrating healed transverse root fractures emerged. Among these was the complex specimen published by Gottlieb in 1922 (9) and translated into English in 1926 (10). Gottlieb was a highly significant figure in Dentistry who also gained his MD in Vienna in 1912 and then specialized in Dentistry. He became the Director of Histology at the Vienna University after World War 1 and followed Wedl's tradition of research into oral biology, with particular reference to pulp histology and pathology. As with many of his Jewish academic colleagues, the advance of Nazism resulted in a diaspora in 1938, principally to the USA – in his case firstly to Jerusulem and ultimately he accepted an academic research position at Baylor University in 1941. The specimen he published in 1922 came from autopsy material and was of a comminuted fracture of a cuspid tooth of a 22-year-old male who had obviously received a shattering blow to the area some time prior to his death. Several fragments of dentin and bone could be observed beyond the fracture line. The fragments of dentin were surrounded by either bone or bundles of connective tissue. Of particular interest was the appearance of the pulp tissue which showed fibrotic changes but there was no evidence of odontoblasts. Secondary cementum deposits were evident in the canal walls as well as in some cracks in the root. Gottlieb's specimen provided the first example of an extreme in healing of a complex comminuted root fracture.

A classic specimen was presented by the well-known caries researcher Howe (11) in 1926 and reproduced by Ottolengui (12) in 1927 (Fig. 1). The tooth was from a 13-year-old boy who had received a blow with a swing 2 years earlier. Hard tissue union was evident at the fracture site consisting of newly formed dentin both into the fracture site and bulging into the root canal. At the periphery, there was an infolding of cementum uniting with the new dentin formation. Commenting at the time Howe stated that 'But it is the new dentin that has splinted this fractured tooth all along the pulpal side and into the fracture. This is the new feature in which this case illustrates and shows what a pulp can do'. How well this healing response was interpreted at the time is reflected in Ottolengui's clinical comment on this case; 'A possible lesson from this experience would teach us that after the fracture of a root, the upper or occlusal fragment should be gently but firmly restored to proper apposition and then splinted into position' (12). Ottolengui also discussed pulp necrosis in the coronal segment of root-fractured teeth, but there was no evidence of the management by endodontic treatment of the affected root canal.

Another specimen of historical importance was reported in 1928 by Boulger (13), a staff member and tutor at Lyola University Dental School. The histological material was obtained from a 45-year-old female who had suffered dental trauma 33 years earlier. The histological sections contained two transversely fractured mandibular incisors that had been surgically removed as a block with the surrounding bone as illustrated diagrammatically by the author (Fig. 2a). Contrasting reparative processes were demonstrated as shown in Fig. 2b, the left incisor showing the root-fractured surfaces covered with layers of secondary

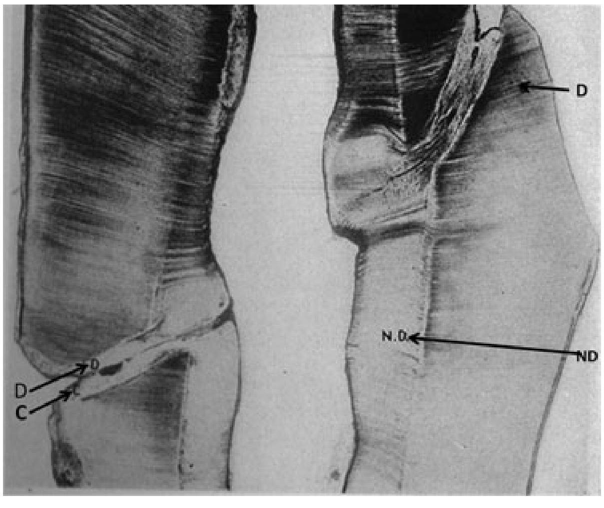

Fig. 1. Vertical section through the root fractured tooth showing the area of the fracture on both sides of the pulp canal. To the right at D is seen normal dentin while at ND new dentin is seen deposited along the wall of the canal, extending also into and 'mending' the fracture. A similar condition is seen on the left of the picture D showing the limit of dentin deposited within the fracture, and at C the infolding of new cementum. Legend and image reproduced with minor textual variations and relabeling from CP Howe 1926 (11).

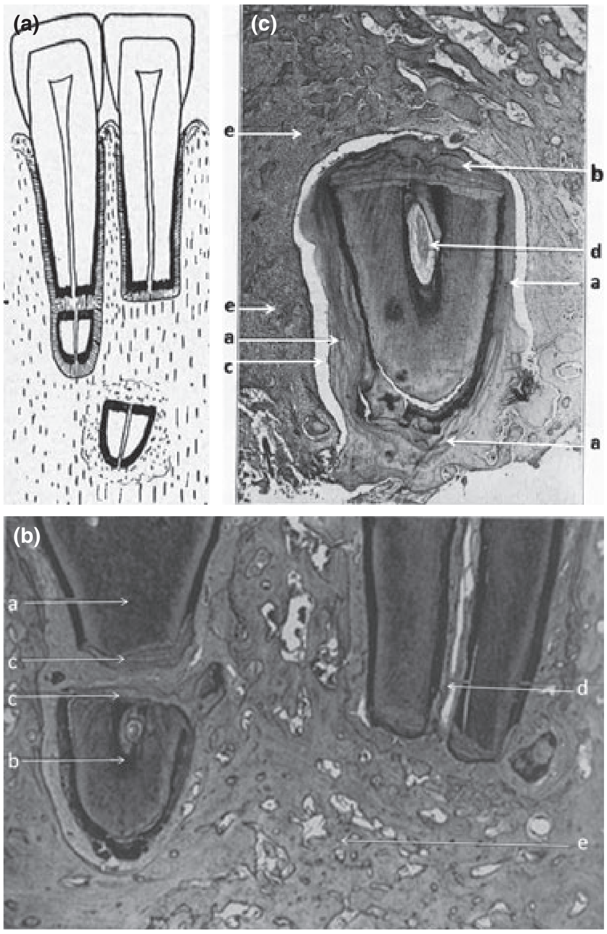

Fig. 2. (a) Diagram of the specimen under discussion; made from roentgenograms and microscopic specimens. Reproduced with permission from Boulger 1928 (13). (b) Fractured roots of both central incisors. (a) dentin; (b) fractured apex of left incisor; (c) secondary cementum deposited on the fractured dentin surfaces; (d) root canal of right incisor; (e) bone deposited on a place formerly occupied by the apex. Legend and image reproduced with relabeling from Boulger 1928 (13). (c) Higher magnification of apically displaced apex from the right central incisor. (a) Cementum around apex; (b) secondary cementum on the fractured dentin surface; (c) artificial space, probably due to trauma due to trauma of surgical trauma; (d) pulp canal with new fibers; (e) scarlike connective tissue around the apex. Legend and image reproduced with relabeling from Boulger 1928 (13).

cementum and fibrous connective tissue interposed between the fractured segments. Peripheral rounding at the fracture site could also be observed indicative of dentin resorption prior to repair by cementum. The right incisor showed similar cementum repair of the fractured surfaces, but there had been considerable apical displacement of the apical segment, which is shown in Fig. 2c. In this incisor, the fractured surfaces of both segments appeared to be surrounded by a periodontal ligament. Serial sections showed viable pulpal tissue in the coronal segments of both teeth but there was evidence of slight degenerative (fibrotic) changes that were attributed to both the trauma and patients age. There was evidence of residual pulp tissue in both heavily calcified apical segments. This case was important in that it showed two distinct patterns of repair of transverse root fractures, namely healing with the interposition of fibrous connective tissue and secondly the interposition of bone between the fractured segments which were surrounded by a periodontal ligament. Despite the growing evidence at that time regarding the healing capacity of teeth with transverse root fractures, it is surprising that the patient involved had been subjected the unnecessary surgical removal of both mandibular incisors. Perhaps the desire for unique histological material clouded the clinical decision making process!

Kronfeld in 1935 (14) published a remarkable example of healing of a transverse root fracture. Also Vienna trained Kronfeld became a research member of staff at Lyola Dental School in Chicago 1928 where he was joined in the late 1930 by other Vienna expatriates, including Harry Sicher, Balint Orban and Joseph Peter Weinmann. Along with American pioneers at Lyola, such as Edgar Coolidge, 'The Vienna group of Illinois' as they became known had a significant influence in the development of oral biology in the USA and worldwide, particularly providing a scientific basis for the newly emerging fields of Endodontology and Periodontology.

The specimen that Kronfeld (14) presented to the Chicago section of the International Association for Dental Research in 1936 came from cadaver material of a 52-year-old male. It consisted of an acute angled transversely fractured maxillary central incisor where the coronal segment had been luxated into a mesiopalatal position, while the coronal extent of the undisplaced apical segment extended to a position close to the alveolar crest. The pulp had survived and could be traced through both segments and there were 'irregular dentin deposits' evident on the root canal walls and a large amount of secondary dentin in the pulp chamber. Between the two fractured surfaces, there was a fibrous connective tissue connection described by Kronfeld 'that closely resembles, and is the functional equivalent of, the periodontal membrane'. This report extended the accepted boundaries of root fracture healing; however, it should be noted that this example would not fulfil current aesthetic demands due to the displaced position of the tooth crown. Kronfeld also discussed the clinical issue of crown discoloration due to the extravasation of blood and the diffusion of blood pigments into dentinal tubules. He appears to have been the first researcher to have discussed transient coronal discoloration in cases of root fracture, pointing out that discoloration is not necessarily a sign of pulp death, stating 'If, however, the pulp tissue recovers, the discoloration remains stationary and may even eventually disappear, as the blood pigment in pulp and dentin is gradually absorbed'. He also pointed out the need to interpret pulp sensibility testing with caution following traumatic injuries, In an earlier publication, he had discussed that a root-fractured tooth basically consisted of two components, the undisturbed apical component, containing vital pulp tissue and the coronal component, where the pulp tissue may either survive and lead to healing or may undergo infective necrosis (15). These were important clinical facts that laid the foundation for the endodontic management of cases of non-healing due to infection by only treating the coronal root canal to the level of the fracture site and leaving the apical segment undisturbed.

Although the patterns of healing of transverse root fractures had emerged by that time through case reports, Dr Heinrich Hammer from the University of Berlin considered that they provided an incomplete picture as the material for those reports had been obtained accidentally from extractions or from cadavers. He instituted the first experimental study to investigate the period of and nature of healing of root fractures in young dogs and published his results in 1939 (16). The dogs were given a high dose of morphine, flaps were raised and the roots of the anterior teeth were fractured at the apical third using a fine chisel, taking care not to interrupt the dental pulp. The flaps were then repositioned and sutured. The dogs were killed after 1, 8, 14, 26 and 28 days and 5, 9 1/2 months and 2 years postoperatively. While it was possible to gain some knowledge regarding the early responses to transverse root fractures from this study, it also showed the difficulty in trying to mimic the clinical situation pertaining to transverse root fractures in humans. Some of the histological specimens showed several dentin splinters, an experimental complication no doubt as a result of the chisel used to create the fractures. The responses reported at 1-day postoperatively were essentially those of oedema and extravasation of red blood cells and some odontoblastic degeneration. By 8 days, the pulps appeared to be healthy and there was an increase in fibroblastic proliferation at the fracture site, which by 14 days postoperatively had resulted in an early callus formation at the pulpal aspect of the fracture site (Fig. 3). While the human response may differ from that of the dog, this finding was of potential clinical significance. Over the ensuing follow-up periods, there was a consolidation of dentin deposition originating from the pulp, but by 5 months increased hard tissue formation in the form of 'osteocement' was reported which increased by 9 1/2 months. The 2-year follow-up evidence was sparse as most of the pulps had degenerated due to the trauma inflicted by the chisel and presumably infection. The surviving specimen showed that most of the defect had been filled with 'osteocement'.

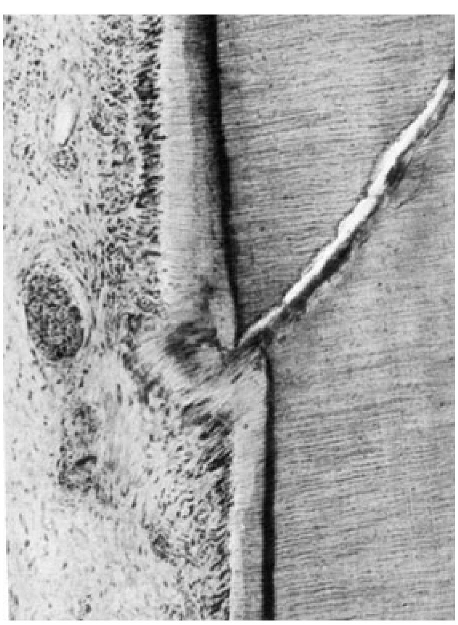

Fig. 3. Formation of a large dentin callus 14 days after experimental root fracture in dogs. Reproduced from Hammer 1939 (16).

In the same edition of The German Dental journal, Deutiche Zahn, Mund und Keiferheilkunde, König (17) published two cases of healed root fractures, the first in a 49-year-old male where he noted that there had been healing originating only from the periodontal ligament, while the pulp had remained passive. He considered this was due to the fact that the pulp was not in its most productive condition. The second specimen showed fibrous connective tissue healing with hard tissue (osteocement) repair on the resorbed dentin at the fracture site.

In 1942, Schindler (18) of Bern, Switzerland, critically reviewed historical reports of root fracture healing and developed a schematic diagram of three healing responses following root fractures as shown in Fig. 4. The healing responses illustrated were the reuniting of the fractured segments by hard tissue as shown in Abb 2, the healing by fibrous connective tissue attached firmly to cementum deposited, after some initial resorption, onto the surface of the fracture surfaces as shown in Abb 3, while Abb 4 depicts fractured teeth where the two segments were considered as separately healed – each segment covered by secondary cementum and periodontal ligament and separated by intervening bone. Schindler's groups were important and formed the basis for a root fracture healing classification developed 25 years later (19). He also presented possibly the earliest example of an attempted treatment of a root-fractured central incisor in which the coronal pulp tissue had become infected. The treatment had consisted firstly of the application of arsenic to the coronal segment, followed by the insertion of chlorine–phenol–camphor–menthol paste. Finally, a root filling of gutta percha and iodoform paste had been placed to the level of the fracture but with some slight overextension. The treatment of the coronal segment failed and the tooth was extracted; however, the radiographic evidence prior to extraction indicated that untreated apical segment remained free of pathosis. The failure had been attributed to the initial use of arsenic.

A further experimental study was reported by Bevlander in 1942 (20), the results of which added little to contemporary knowledge and only emphasized the importance of experimental design when investigating transverse root fractures. He used forceps to inflict a variety of crown root, longitudinal, oblique and transverse root fractures in the deciduous molars of young dogs that were killed 3 weeks later. This study using such a crude methodology was reported to a general meeting of the International Association for dental

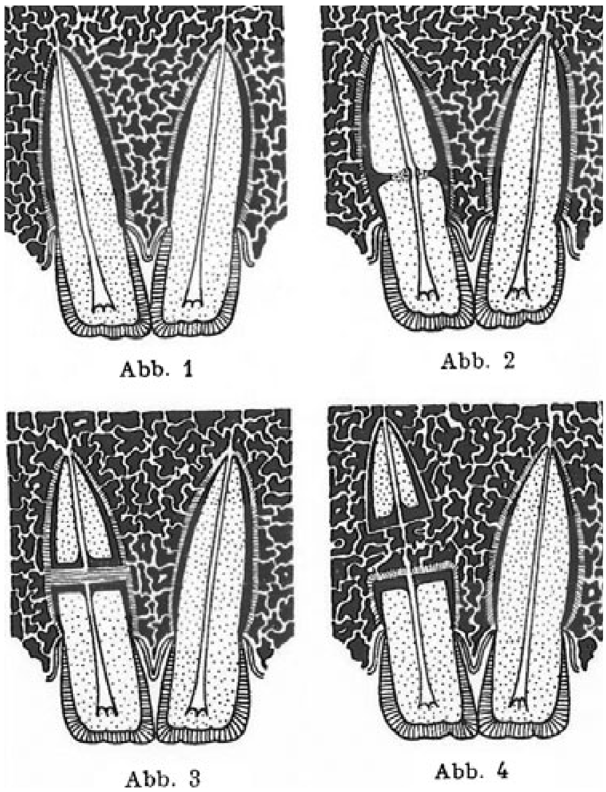

Fig. 4. Schindler's schematic representation of various healing processes following root fracture. Figure (Abb) 2 reunification of the tooth with the deposition of dentine and secondary cement from the periodontal ligament. Figure (Abb) 3 Healing by connective tissue with the fracture surfaces coated with secondary cement- leading to a connective tissue-like ankylosis. Figure (Abb) 4 Separation of the fractured segments replaced by bone with each remnant separately healed. The fractured dentine surfaces are covered with secondary cement and the periodontal ligament surrounding the coronal segment has an orientation corresponding to functional forces with while the apical segment with a lack of functional loading has a 'relaxed tissue connection'.

research and can only be described as an abuse of young dogs and of dental research.

As the first half of the twentieth century drew to a close, having endured the horrors of two world wars, the accumulated knowledge regarding the healing responses to transverse root fractures had reached a high level of understanding that could be applied clinically. However, therapy for root-fractured teeth with nonhealing due to infective pulp necrosis in the coronal segment was in its infancy.

Further case reports with histology emerged over the next 12 years (3, 21–27), but it was the report published by Blackwood (25) of two maxillary central incisors fractured 6 months earlier that provided the most significant evidence of two contrasting reparative healing responses. The teeth and surrounding bone were removed surgically in a block resection as part of an overall orthodontic treatment plan. The resultant histological findings, which were meticulously and elegantly reported, provided an unique insight into early healing responses of root-fractured teeth in humans. In one of teeth, there was a broad band of well-vascularized fibrous connective tissue interposed between the fractured segments and this was continuous with the periodontal ligament (Fig. 5a, b). There was evidence of resorption of the fractured dentin surface on the labial aspect of the tooth. In addition, internal resorption, which had been partly repaired by cellular dentin, could be noted within the root canal walls at the fracture site of both fractured segments. The latter finding was significant as it appeared to represent a phase in an overall healing process and has relevance to subsequent clinical and radiological reports of transient internal resorption prior to healing, usually with calcified tissue (28–30). The second incisor specimen demonstrated bone and cellular fibrous connective tissue interposed and extending into both the coronal and the apical segments. Again the fibrous connective tissue was continuous at the periphery with the periodontal ligament. The pulpal changes in both teeth were similar with fibrosis, and the laying down of calcified tissue on the canal walls. This hard tissue was labelled cellular dentin, due to its histological characteristics. In some areas, there had been the deposition of somewhat irregular tubular dentin indicative of some recovery of odontoblasts particularly in the apical segment. The author noted that during the reparative processes the vascular supply to the coronal segment came both from the apical segment and from anastomoses at the fracture site.

Thus, it could be proposed that the work of the early pioneers dating from the 19th century to 1959 laid solid foundations through histological reports and studies for the rationalization and clinical recognition of the healing processes involved in transverse root fractures. From a therapeutic viewpoint, articles dealing with the endodontic management of nonhealing transverse root fractures were published in 1957 by Lindahl (31) and by Michanowicz in 1963 (32). Hitherto treatment, generally, was not carried out on nonhealing root fracture cases and extraction of these salvageable teeth was the norm.

In 1967, Andreasen and Hjørting-Hansen (19) published a landmark prospective study of 50 root-fractured teeth that were evaluated clinically and radiographically. They also reported on 12 histological specimens. For the study, the authors adopted a modification of Schindler's classification of healing of transverse root fractures. The four groups were defined as follows: (1) healing with calcified tissue, (2) healing with interposition of connective tissue, (3) healing with interposition of bone and connective tissue and (4) healing with interposition of granulation tissue.

Although the fourth group indicated a 'healing' response the authors in the same publication stated that the interposition of granulation tissue denoted nonhealing and outlined the need for endodontic management of the coronal segment. This was reinforced by their histological reports of nine teeth from group 4 where all specimens showed granulation tissue and proliferating epithelium between the tooth fragments and pulp necrosis, presumably due to infection in the coronal

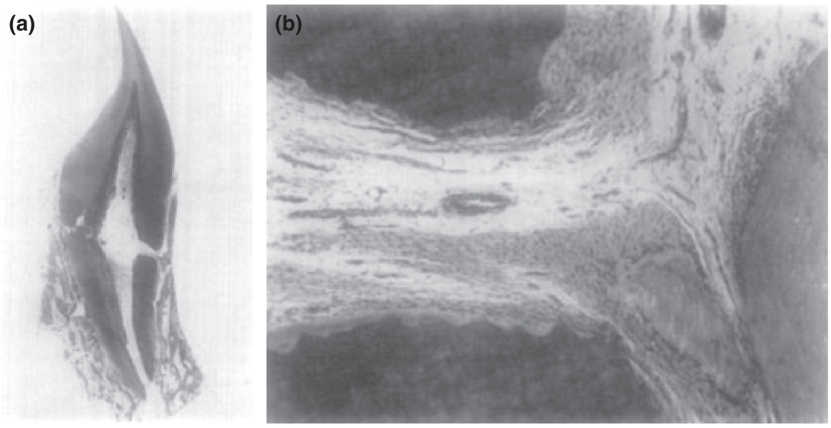

Fig. 5. (a) Labio-lingual section of the right central maxillary central incisor showing the fracture of the root. Legend and image reproduced from Blackwood 1959 (26). (b) Labial extremity of the fracture in the right maxillary incisor. New bone formation is seen in the periodontal membrane, right. Legend and image reproduced from Blackwood 1959 (26).

segment and vital tissue in the apical segments. This study formed one component of the comprehensive coverage of all dental injuries contained in the first 'Traumatic injuries of the teeth' textbook edited by Andreasen in 1972 (33). Each subsequent edition has updated research into dental traumatology, including root fractures. Now in its fourth edition, with 44 contributors, and edited by Jens Andreasen, Fran Andreasen and Lars Andersson, this textbook has made a monumental contribution to the field of dental traumatology over the past 40 years.

While the histological reports and studies from preceding years had largely defined the healing responses following root fracture, the dynamics and cellular contributions to hard tissue repair were further investigated by Tullin (34) in 1968, Bouyssou et al. in 1970 (35) and Michanowicz et al. in 1971 (36). The first author considered that 'the pulp has sometimes the capacity of overbridging a gap in the dentin with new hard canalized tissue, that is secondary dentin, but mostly the hard tissue found in the fracture space consists of cementum, bone or both together and is probably derived from the periodontal membrane'. He also suggested that hard tissue which is impossible to classify could be termed sclerotic tissue or undifferentiated mineralized tissue. The second authors suggested that of the three types of hard tissue healing, the deposition of osteodentin or osteocement or both, filling the pulp and the space between the segments is often the end result of the other two recognized hard tissue healing responses namely a 'sealing' callus on both fragments followed by the deposition of osteodentin onto this matrix or the formation of a ring of new cementum between the fragments leaving the pulp lumen more or less permeable throughout. The third authors presented the results of a histological evaluation of six specimens from which they proposed that cementogenic repair was the principal healing process in root-fractured teeth and that the pulp was not necessary for root repair.

In an attempt to further investigate the healing responses following transverse root fractures, some experimental studies have also been carried out in the late 19th century using either baboons (37) monkeys (38) or dogs (39) employing a variety of techniques designed to create transverse root fractures. In the baboon study (37), the method of inducing a transverse root fracture differed to that employed in 1939 by Hammer (16), in which flaps were reflected and a chisel was used to inflict the injury, with care being taken not to injure the pulp. In the Michanowicz study, the chisel was driven through the alveolus and root. While this technique should have resulted in complete comminuted fractures, some of the specimens had received only a small root surface defect. Those with a comminuted fracture showed dentin splinters at or more remote from the fracture site. The responses observed in a two part series of experiments varied from 24 h to 3 months in part 1 and 6 months to 9 months in part 2. In part 1, fibrous connective tissue repair occurred within the first 3 months, beyond which osseous tissue was observed between the fractured root segments. From the part 1 study, Michanowicz concluded that the periodontal ligament appeared to have the major role in the repair process. In part 2 of the study, there was a contrasting conclusion, namely that the pulp and the periodontium probably play a role in the healing process. This resulted from observations of hard tissue healing between the fractured segments in three specimens and partial union in two. His other observations of resorption of the surfaces of the fractured segments and healing with cellular cementum and pulpal responses varying from normal to fibrotic or necrotic and the deposition of cementum, dentin or both on the walls of both segments were consistent with earlier reports as reviewed. The difference between the first and second studies in respect to hard tissue union is difficult to reconcile and may be the result of the experimental problems resulting in variations in the root fracture inflicted. In the study carried out in African green monkeys (38), Hammer's technique was employed; however, the authors noted the difficulties in inducing reproducible root fractures without causing damage to adjacent teeth. This was confirmed by the published image of two incisors one with a mid-root fracture, while the adjacent tooth had an oblique fracture extending from the mid-root level to the level of the cemento–enamel junction. Healing by either the interposition of dense connective tissue or bone and connective tissue was reported but no hard tissue union was evident over the 6-month observation period. In the third study, carried out in dogs (39), a horizontal transverse cut was made through the roots of all teeth from the molars to the incisors with a saw blade, creating a wound that could be equated with that of a surgical osteotomy involving the apices of teeth for which there had been a previous report (40).

All these experimental studies have revealed the difficulty in replicating in animals root fractures inflicted in humans where a blow perpendicular to the tooth causes not only a root fracture but also some movement of the coronal section of the tooth in the alveolus. Although dentine splinters have been observed in some human histological reports, their presence in most of the histological sections of these animal studies indicates methodological difficulties in this type of experimentation. Tullin (34) queried the validity of Hammer's 1939 experiments and it could be argued that the more recent studies could also be considered to be of questionable relevance to human root fracture responses. In addition, the ethical approval for such animal experimentation is currently unlikely to be granted in most countries.

Since the early 1970s extensive clinical studies have investigated factors affecting the type of healing of transverse root fractures, including age, stage of root development, location of the fracture, mobility and dislocation of the coronal fragment and the diastesis or separation between the fractured fragments with stretching or rupture of the pulp at the fracture site (1, 2, 41–45). Treatment variables such as optimal repositioning and the application of a nontraumatic splint that allows a degree of flexibility have also been reported to be associated with a healing response (2, 41, 46).

The endodontic management of the coronal segment in cases of nonhealing has also been extensively investigated since the early foundations. Andreasen (47) in 1971 reported on conventional endodontic treatment in the coronal segment of 11 nonhealing root-fractured teeth, but it was Miomir Cvek in 1974 who published the first extensive study in which calcium hydroxide had been used in the treatment of nonvital permanent incisors including the treatment of teeth with intra-alveolar root fractures (48). Cvek continued his extensive clinical studies over the following 34 years (1, 2, 49, 50), completing his last report on the prognosis for root fractures with co-authors Jens Andreasen and Georgios Tsilingaridis, just prior to his death in 2008 (51). Cvek's legacy has been his extensive dossier of documented cases at the Eastman Dental Institute in Stockholm. His long-term collaborator Jens Andreasen and co-researchers have continued to analyse his material and have provided further valuable and favourable prognosis data in a recent article (45). Mineral trioxide aggregate (ProRoot® MTA Dentsply) introduced by in the mid-nineties has been used to fill the apical few millimetres of the coronal segment of nonhealing root fractures with the same aim as with the application of calcium hydroxide of promoting a hard tissue barrier at the extremity of the fractured coronal segment and promoting healing of the periradicular tissues (52–56). Results with both therapies indicate a high level of success in retaining root-fractured teeth compromised by pulp necrosis due to infection in the coronal segment and as such have advanced clinical knowledge and management.

In conclusion, the early histological investigations into the healing processes of transverse root fractures, as reviewed, undoubtedly laid sound foundations and a legacy for the more recent clinical studies that have provided the dental profession with highly effective and predictable management strategies for the victims of this type of dental injury.

Case report 1. Illustrating healing by hard tissue formation

In 1991, a female aged 9 years fell and fractured the root of her maxillary left central incisor at the cervical level. The mobile crown was splinted by her dentist but 11 days later, the bonded splint was lost and was replaced. At that time electrical sensibility testing was positive but at a reduced level compared with the contralateral central incisor. Further bonding was required 3 weeks later. Two and a half months later, a radiograph taken at the School dental clinic showed the low transverse cervical root fracture (Fig. 6a). The dentist decided to permanently splint the tooth to the contralateral central incisor surfaces using 0.03 gauge arch wire bonded with composite resin on the palatal surface. Eight days later the patient received a further blow to her face and when examined the right maxillary central incisor was tender but the splint was intact. The tooth was reviewed again 8 months later, when it responded positively to pulp sensibility testing. In 1996, aged 14, the patient was assessed for orthodontic treatment, and on the basis of a panoramic film (Fig. 6b), the orthodontist elected to remove this tooth as part of the overall orthodontic management.

The tooth was extracted intact and became available for histological examination some days later but no fixation had been carried out during the intervening period. Photographs of the extracted tooth demonstrate that the transverse root fracture extended from 2 mms above the cemento–enamel junction on the labial surface to 3 mms below the cemento–enamel junction on the palatal surface (Fig. 7a). They also revealed hard tissue between the fractured segments but the original contours of the tooth had not been fully restored evidenced by the narrow gutter at the periphery of the tooth (Fig. 7b). Radiographs taken from the labial and lateral aspects revealed that the tooth had not been perfectly aligned axially and vertically (Fig. 7c). The radio-opacity of the hard tissue deposited at the fracture site was significantly less than the normal tooth structure and showed as an apparent silhouette image of the original fracture.

The extracted tooth was ultimately fixed in 5% formalin for 24 h, decalcified, embedded, serially sectioned at 5 μm and stained with H & E and van Giesson stains. Figure 8a shows a low magnification view of a transverse section of the tooth, which revealed hard tissue formation between the fractured segments and bulging into the root canal on both the labial and palatal aspects. Despite the delay in fixation, some details of pulp tissue can be seen. The hard tissue deposited

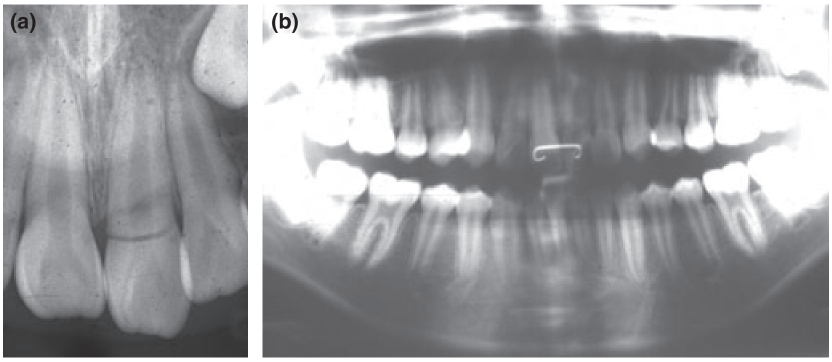

Fig. 6. (a) Radiographic image showing a cervically located root fracture in the maxillary left central incisor of a 9 year old female. (b) Panoramic image taken 5 years later at age 14 showing the previously root fractured left central incisor and the wire/composite splint in position.

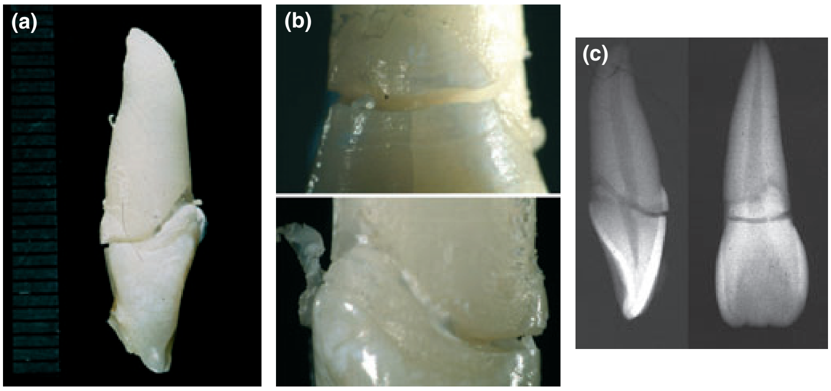

Fig. 7. (a) Proximal view of extracted tooth. (b) High power labial and proximal views of the extracted tooth. (c) Radiographic images taken from the proximal and labial surfaces.

on the labial aspect of the tooth had two distinct patterns of development Towards the labial surface, the deposition appeared to fibrillar in appearance interspersed with a number of small and somewhat larger channels containing some soft tissue/cell inclusions (Fig. 8b). On the pulpal aspect, the hard tissue deposition consisted of a deeper area of irregular tubular dentin and an outer layer of more regular tubular dentin with varying orientations, and an overlying layer of odontoblasts (Fig. 8c, d). On the palatal aspect, there appeared to be three distinct patterns of hard tissue formation (Fig. 8e, f). On the pulpal side, the appearance was similar to that which had occurred on the labial aspect where two patterns of hard tissue formation were evident – the fibrillar and the tubular. The third pattern on the periodontal ligament aspect appeared as a relatively uniform structureless deposit that could be described as sclerotic calcification. There was also some evidence of dentin resorption at the fracture site prior to hard tissue repair.

Case report 2. Illustrating healing by dense fibrous connective tissue formation

In May 1982, an 11-year-old male received a blow to his maxillary right central incisor and the tooth was reported to be slightly mobile. Two weeks later, the tooth was knocked again, followed by yet another blow 3 weeks later where it was recorded by the School Dentist that the tooth appeared to have been intruded 1 mm and was very mobile. The tooth stabilized and a radiograph taken in September 1982, and after 14.5 weeks, the initial injury showed evidence of healing of a previous mid/cervical root fracture indicated by calcification in the coronal pulp chamber and the appearance at the fracture site (Fig. 9a). After an orthodontic consultation at the time, it was decided that the tooth be monitored clinically and radiographically until definitive orthodontic treatment at age 14. A clinical photograph of the patient at age 14 showed a large overjet associated with a Class II malocclusion (Fig. 10). A periapical radiograph of the maxillary right central incisor taken at that showed slight further calcification in the apical segment, a rounding of the periphery of the fractured surfaces and no obvious periradicular pathosis (Fig. 9b). Clinically, the tooth appeared to have a normal colour and there was minimal coronal mobility. It was concluded on the evidence available that the root fracture had healed by the interposition of fibrous connective tissue. At that time several orthodontic treatment options were considered; however, it was finally decided that the affected tooth would be extracted and followed by orthodontic treatment for the malocclusion and closure of the space by repositioning the lateral incisor and cuspid tooth.

The tooth was extracted with both segments intact and a photograph of the tooth after fixation is shown (Fig. 11a). The tooth was subsequently prepared for histological evaluation as detailed previously. A low magnification image shows the entire tooth that had been sectioned mesio-distally with dense fibrous connective tissue interposed between the previously fractured segments (Fig. 11b). Extensive calcification is evident in the coronal and radicular segments, but

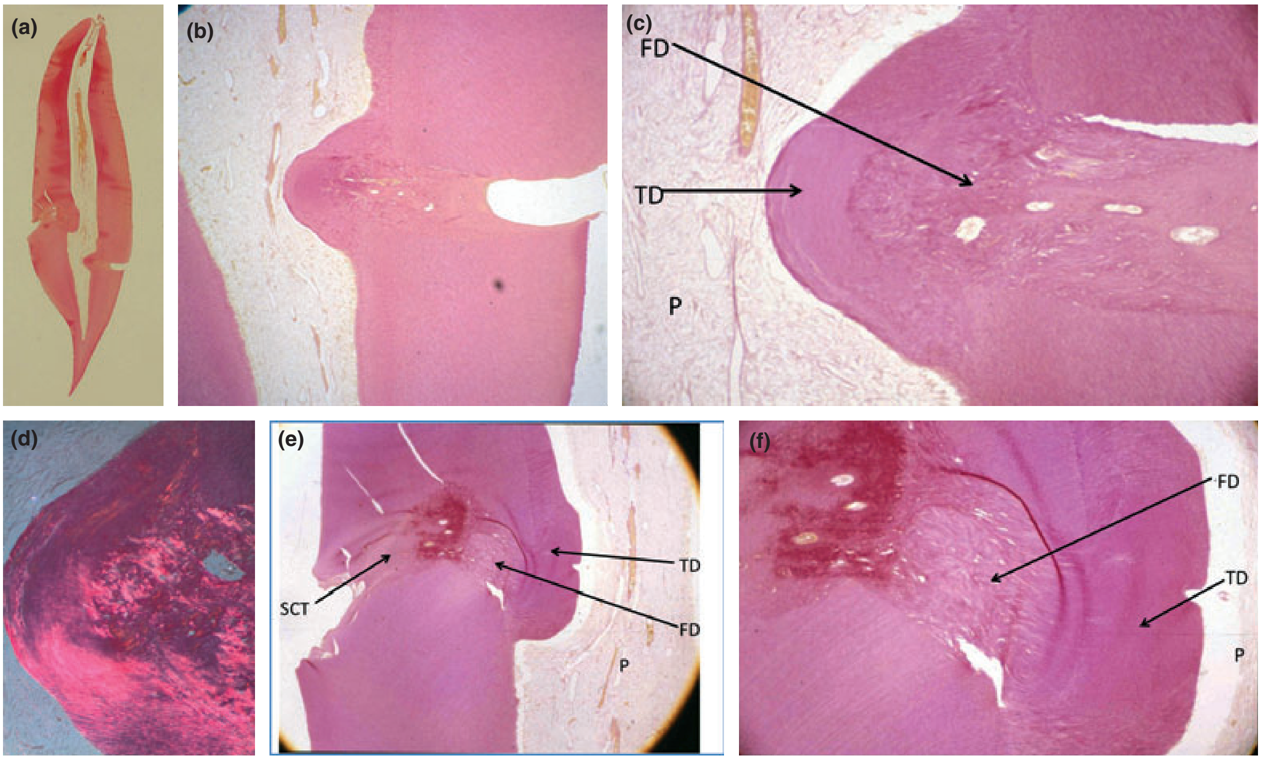

Fig. 8. (a) Sagittal histological section in a labio-palatal plane showing pulp and hard tissue deposition between the fractured segments on the labial and to a greater extent on the palatal aspect. Van Gieson stain orig magnification ×4. (b) Labial section showing hard tissue deposition between approximately half of the fractured dentin surfaces and bulging into the root canal space. Van Gieson orig magnification ×10. (d) Polarised light view of the pulpal extremity of dentin deposition showing the tubular orientation and deeper irregular hard tissue formation with cell/tissue inclusions. Orig magnification × 25. (e) Palatal section showing hard tissue deposition between the majority of the fractured dentin surfaces and budging into the root canal. The calcified tissue tissue deposits consist of tubular dentin (TD) fibrillar dentin (FD) with cell/tissue inclusions, considered to be of pulpal origin (P), and sclerotic calcified tissue (SCT), considered to be of periodontal ligament origin. Van Gieson orig magnification ×10. (f) Higher power view of the calcified tissue considered to have been pulpally deposited showing further details of the orientation of the dentinal tubules in the tubular dentin layers (TD) and the deeper fibrillar dentin layers (FD) orig magnification ×20.

there is some evidence of retained pulp tissue in both segments and there is fibrous connective tissue interposed between the previously root-fractured dentin surfaces. A higher magnification shows dense fibrous tissue with a parallel orientation to the fractured root surfaces and evidence of repaired resorption by hard tissue (Fig. 11c). Using Van Gieson stain, the interposed tissue showed further details of the dense connective tissue with minimal vasculature and some extravasated red blood cells, no doubt the result of the extraction trauma (Fig. 11d). Using polarized light, Sharpey's fibre insertion into the repaired fracture surfaces could be demonstrated (Fig. 11e from the section outlined in Fig. 11d) with the orientation being oblique to fractured surfaces.

Discussion

Case report 1 has some significant and possibly unique features of importance to the understanding of the role of the pulp and the periodontal ligament in healing of a transverse root fracture with calcified tissue. The clinical, radiological and postextraction evidence indicates that the apex of the tooth was immature and that the original transverse fracture extended from 2 mms above the cemento–enamel junction on the labial surface to 3 mms below the cemento–enamel junction on the palatal surface. Taking into consideration, the age at which the original injury was inflicted, it could be concluded that the fracture was supragingival on the labial aspect extending to subgingival on the palatal surface. As a result, the calcific tissue observed histologically on the labial aspect of the specimen (Fig. 9a–c) can be attributed solely to pulpal deposition, while on the palatal aspect, the calcified tissue that has two contrasting components as shown in Fig. 10a, b is indicative of both pulpal and periodontal involvement. As the calcified tissue deemed to be of pulpal origin on both the labial and palatal aspects have similar morphological characteristics, it could be deduced that the initial 'callus' or bridging was laid down by pulpal cells – firstly a fibrillar calcified tissue followed by the deposition of tubular dentin with a 'sunray' appearance bulging into root canal space. It could also be concluded that the relatively structureless hard tissue observed on the palatal aspect had been laid down onto the initial 'callus' by cells of periodontal origin. As suggested by Tullin (34), this relatively structureless calcified tissue

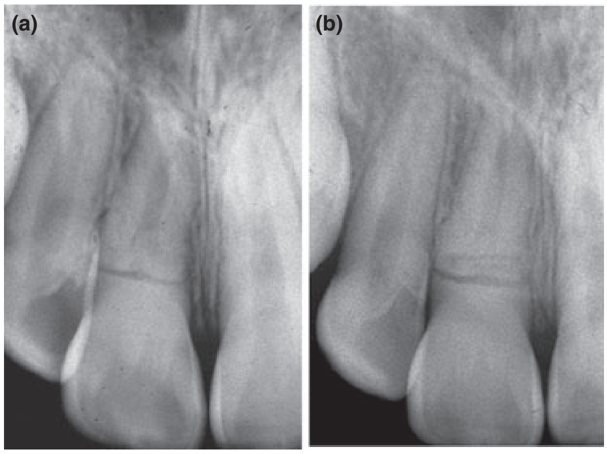

Fig 9. (a) Periapical radiograph of an 11 year old male taken 14.5 weeks after the original injury showing evidence of healing of a mid/cervical root fracture of the maxillary right central incisor. (b) Periapical radiograph taken at age 14 showing slight increase in calcification within the canal of the apical segment, slight rounding at the periphery of the fractured root surfaces and no obviuos periradicular pathosis.

Fig. 10. Facial appearance of the 14 year old male taken 3 years after a blow which caused a root fracture of his maxillary right central incisor. A lateral view shows a significant maxillary incisor overjet.

could be termed sclerotic mineralized tissue. The end result in this case has been a united tooth with a narrow unfilled gutter or deficiency extending around the periphery of the tooth. In cases where there has been pulp survival following a transverse root fracture, this specimen would seem to provide an answer the question as to whether it is primarily pulpal or periodontal ligament participation in the healing process with calcified tissue or whether it is a combination of both. This specimen provides evidence of a dual involvement, the pulp providing the initial callus followed by hard tissue formation from cells derived from the periodontal ligament.

Case report 2 has similarities to the case presented by Boulger (13) in 1928 in that a significant feature was the initial resorption of the fractured dentin surface of both the coronal and the apical segments, followed by repair by the deposition of a calcified tissue as shown in Fig. 11b,c. As part of this reparative process, dense fibrous tissue, laid down in a parallel orientation between the fractured segments by cells derived from the periodontal ligament, was attached by Sharpey's fibres into the newly deposited calcified tissue. This is of clinical significance as the resultant fibrous union represents a functional unit, capable of both physiological and if necessary orthodontic movement. Some early authors suggested that this type of fibrous tissue union constituted a pseudoarthrosis (4, 17). However, this term is not applicable as it indicates the formation of a false joint where a fibro-cartilagenous cavity is lined with synovium producing synovial fluid (57). The original injuries occurred at age 11 when the apex of the tooth would have been nearing maturity and that factor combined with the likely degree of displacement of the coronal segment has been shown to favour fibrous connective tissue healing as opposed to calcified tissue repair (41, 42). This healing pattern is usually associated with a moderately injured pulp where it is necessary for revascularization of the coronal segment to occur before any pulpal tissue can participate in the healing response. This time lag allows periodontally derived cells to dominate the healing response (41, 42). In the present case, the extensive calcification evident within the root canals along with pulpal fibrosis is consistent with earlier reports.

Clinical implications

Both specimens demonstrating positive healing responses with either calcific or dense fibrous tissue became available because of orthodontic treatment plans made 21 and 30 years ago, respectively. In the first case, it seems that the decision to extract the tooth was made on the basis of a panoramic film where the image of the previously root-fractured incisor could be seen but was relatively blurred. A recent study has shown the importance of supplementing panoramic radiography with periapical radiographs to diagnose teeth with anatomical anomalies, root fractures and root resorption (58). Nevertheless, the difference in radiopacity between normal tooth structure and calcific reparative material laid down following a root fracture can conceivably lead to some confusion when diagnosis is based on radiographic grounds alone (3). This is clearly illustrated in Fig. 7 and indicates the importance of a thorough clinical assessment, involving pulp sensibility, mobility testing and careful periodontal probing. While pulp sensibility testing will be affected by the degree of root canal calcification, the combination of the other assessments should indicate the viability of retaining such a tooth, particularly if orthodontics is planned. A recent study into the influence of type of healing and location of fracture on tooth survival rates has indicated that teeth with healing by calcified material have an excellent prognosis regardless of the position of the fracture (45). Nev-

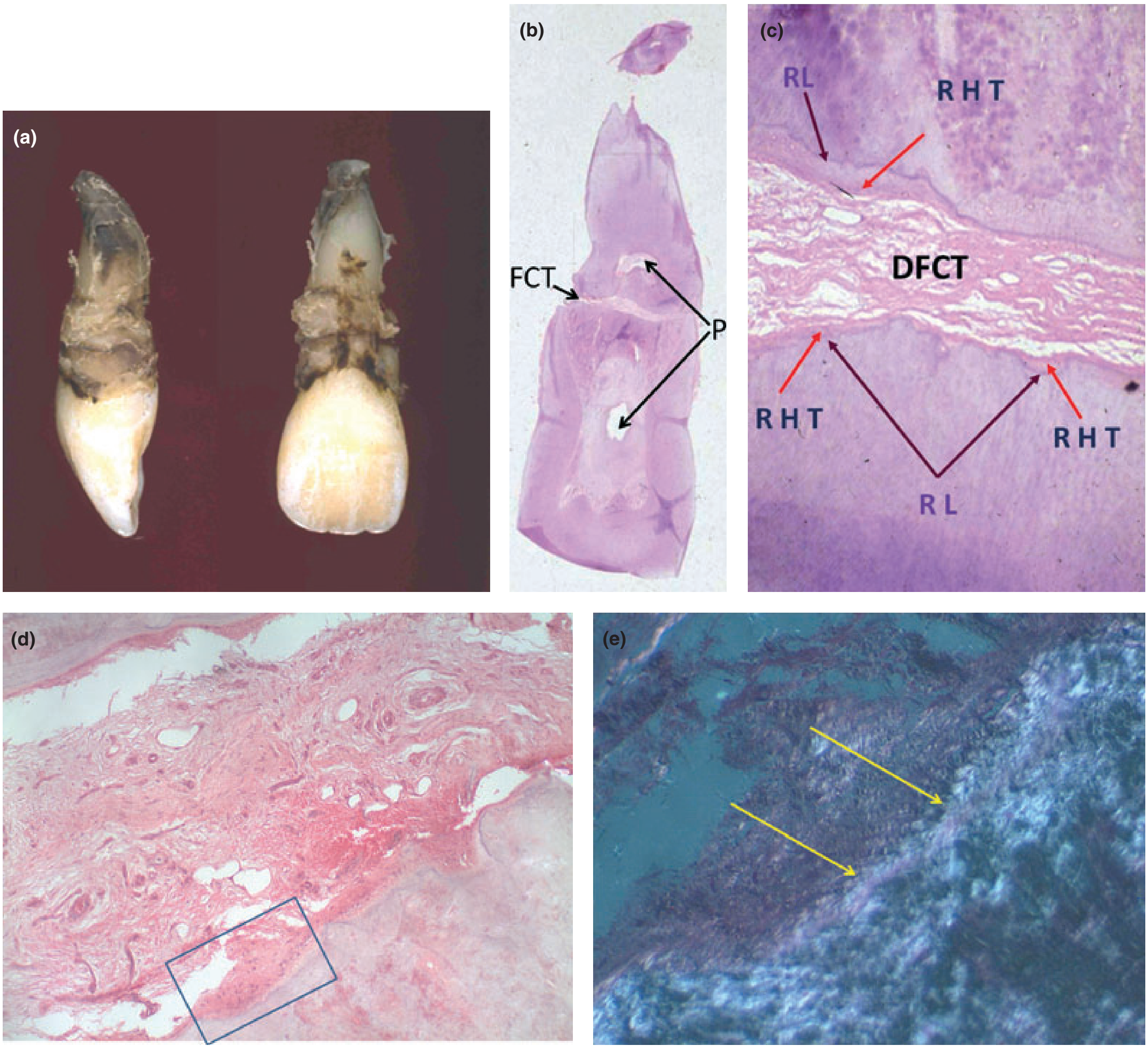

Fig. 11. (a) The intact central incisor after extraction and formalin fixation. (b) The histological appearance of the extracted tooth sectioned in a mesio-distal sagittal plane showing the interposition of fibrous connective tissue (FCT) calcification of the root canals but evidence of residual pulp tissue (P) H&E orig magnification ×4. (c) View of the fracture site showing dentin resorption lines (RL) repaired with reparative hard tissue (RHT) and the interposed dense fibrous connective tissue (DFCT) H&E orig magnification ×10. (d) Higher power view showing dense connective tissue generally with a parallel orientation to the fractured dentin surfaces which show reparative hard tissue laid down on previously resorbed dentin. There is minimal vascularity but some extravasated erythrocytes are evident. Van Gieson orig. magnification ×20. (e) Highlighted section from Fig. 11d using polarised light to demonstrate Sharpey fibre insertion into the reparative hard tissue (arrows). Orig magnification ×40.

ertheless, patients requiring orthodontics because of Class 2 malocclusion with proclined maxillary anterior teeth may be more susceptible to secondary trauma as occurred in this case. The splinted central incisor was tender after the additional trauma but was otherwise intact. Whether or not the bonded splint provided additional support and so avoid a further fracture is conjectural but permanent splinting on the palatal aspect of such low root fractures is worthy of consideration as indicated in a recent publication (45).

The radiographic appearance of case 2 at the fracture site is similar to that observed in case 1 and so the diagnosis of healing with fibrous connective tissue relies on other radiographic and clinical evidence. The calcification in the coronal segment of case 2 is consistent with the dynamics of the healing with fibrous connective tissue. Mobility testing usually indicates some greater degree of movement compared with a contralateral incisor; however, in this case, it was minimal. A recent study that monitored tooth mobility in teeth with connective tissue repair showed that mobility reduced over time suggestive of a greater union of the interposed fibrous connective tissue with the fractured dentin surfaces by Sharpey's fibres (59). Thirty years ago, the decision to extract this tooth rather than subject it to orthodontic treatment was obviously made on the basis of the limited knowledge available at that time. However, in hindsight, the fibrous connective tissue union in this central incisor should have provided the opportunity for orthodontic treatment without the complication of anterior tooth removal. Recent reports confirm the viability of orthodontic tooth movement in such cases (60–63).

In summary, these two case reports of healing of root fractures with either calcified or dense fibrous tissue provide further evidence regarding the cellular responses involved and the clinical implications relating to the diagnosis and conservation of teeth that have suffered this type of dental injury.

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