CLINICAL RESEARCH

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Success and Survival of Endodontically Treated Cracked Teeth with Radicular Extensions: A 2- to 4-year Prospective Cohort

SIGNIFICANCE

Cracked teeth with radicular extensions may have higher success rates than previously thought. Using modern endodontic techniques, placing deep intraorifice barriers, and following specific postoperative protocols may improve outcomes for these cases.

ABSTRACT

Introduction: There are no long-term, prospective clinical studies assessing outcomes of endodontically treated cracked teeth with radicular extensions. The purpose of this prospective study was to examine the 2- to 4-year success and survival rates of endodontically treated, coronally restored, cracked teeth, specifically where the crack extends beyond the level of the canal orifice internally. **Methods:** Seventy consecutive teeth requiring endodontic treatment with cracks extending to the level of the canal orifice and up to 5 mm beyond were included in the cohort. Treatment was performed by a single endodontist using current techniques, and cases were followed over time. Specific treatment and posttreatment protocols were used. A tooth was "survived" if it was present, asymptomatic, and functional. The category of "success" was given to a case if strict radiographic and clinical criteria were met. **Results:** Fifty-nine teeth were eligible for survival analysis, and 53 teeth were available for success analysis. There was a 100% survival rate in the first 2 years and 96.6% survival up to the 4-year period; 90.6% were classified as "success" in the 2- to 4-year term. No significant differences ($P < .05$) were found for periodontal pocketing (up to 7 mm) at the site of the crack, marginal ridge involvement, crack depth, or pretreatment diagnoses. **Conclusions:** This study showed that the success and survival rates for cracked teeth with radicular extensions may be similar to endodontically treated teeth in general and may be higher than previously reported in cracked tooth studies. Treatment outcomes in cracked teeth with radicular extensions may be improved by using the following protocols: microscope-assisted intra-orifice barriers placed apical to the extent of the crack, complete occlusal reduction, specific postoperative instructions, and expeditious placement of a full-coverage restoration. *(J Endod 2019;45:848–855.)*

KEY WORDS

Cracked teeth; endodontic; intraorifice barriers; radicular cracks; success; survival

A cracked tooth is defined as a tooth with 1 or more incomplete, longitudinal fractures originating in the coronal tooth structure and extending apically; the crack typically orients mesiodistally, involves the marginal ridges, and includes the proximal surfaces of the tooth[1]. Posterior teeth are most commonly affected, with the predominant tooth types being the mandibular molars, maxillary molars, and maxillary premolars[1–5]. Although cracks usually have a vertical orientation coronoapically and can extend onto root surfaces, they are not to be confused with vertical root fractures. Vertical root fractures occur by and large in endodontically treated teeth, originate within the root, generally orient in the buccolingual direction, and often carry a hopeless prognosis[1,6].

Symptomatic cracked teeth can present diagnostic and restorative challenges for both the dentist and the endodontist[7]. Accurate pulpal diagnosis can assist in making appropriate endodontic treatment decisions. For cracked teeth presenting with a diagnosis of symptomatic reversible pulpitis, full cuspal coverage is the treatment of choice without the need for endodontic intervention in the majority of cases[3,4,8]. Conversely, endodontic treatment is required before placement of a coronal restoration if

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presenting symptoms, diagnostic testing, and radiographic evaluation reveal some form of endodontic disease[4,8,9].

There is a lack of research-based guidelines concerning the restorability and management of teeth with cracks extending onto the root surface. Some authors recommend extracting these teeth[4,8,9] with little to no supporting evidence despite the fact that patients generally have a strong desire to save their natural tooth[10]. Interestingly, subsets of cracked tooth studies have shown longevity in subgingivally cracked teeth with survival rates ranging from 66.7% to 88.3% at 2+ years[11–13] demonstrating that saving these teeth may be an option. To date, there are no studies looking prospectively at outcomes of cracked teeth with radicular extensions.

The purpose of this prospective study was to examine the 2- to 4-year success and survival rates of endodontically treated, subgingivally cracked teeth in an endodontic private practice using current techniques. This cohort specifically included only those cracks extending into radicular dentin, beyond the level of the canal orifice internally, and into periodontal structures externally.

MATERIALS AND METHODS

Study Design and Patient Enrollment

A prospective study was designed using the Strengthening the Reporting of Observational Studies in Epidemiology guidelines for cohort studies[14], and data were gathered following the American Association of Endodontists' Guidelines for the Methodology of Cracked Tooth Studies[15]. The inclusion criteria were as follows: posterior cracked teeth where internally the radicular extent of the fracture was observed to be at the level of the canal orifice and up to 5 mm beyond. All study teeth had to be in occlusal function with an opposing tooth. Exclusions were split teeth, cracks extending completely across the pulpal floor, and cracks limited to coronal dentin. Pretreatment data were recorded and included age, sex, tooth type, orientation and surface location of the cracks, materials and surfaces of existing restorations, presence of periodontal pocketing ($\geq$5 mm), pulpal and periapical diagnoses, and radiographic presence or absence of periradicular lesions. Consecutive patients presenting over a 1-year period and fulfilling the inclusion criteria were enrolled. The study population consisted of 70 teeth in 69 patients.

In addition to gathering the clinical data and patients' subjective history of symptoms, thorough diagnostic pulp testing, periapical testing, and digital radiographic interpretation were performed. Bite stick responses and periodontal probing depths were also recorded. After endodontic pathosis was confirmed, root canal treatment or retreatment was performed by one board-certified endodontist in private practice.

Clinical Procedures

Informed consent was obtained after treatment alternatives and the uncertain prognosis were discussed. Local anesthetic was then administered, and rubber dam isolation was achieved. Endodontic treatment was initiated through a conservative access cavity after all caries, and compromised restorative materials were removed. A dental operating microscope (Global Surgical Corporation, St Louis, MO) was used for every step of the procedure. The number of cracks was counted as those radiating outward from the endodontic access cavity. In retreatment cases, obturation materials were removed with rotary nickel-titanium files. In all cases, the canals were chemomechanically prepared with rotary instrumentation (ProTaper S2 and Vortex .04, Dentsply Sirona, York, PA) and RC-Prep (Premier Dental Product Co, Plymouth Meeting, PA). Irrigation with 2.6% sodium hypochlorite with sonic activation (EndoActivator, Dentsply Sirona) and final irrigation with 17% EDTA and 2% chlorhexidine were performed. The internal depth of the radicular crack was measured from the level of the canal orifice using a periodontal probe under the microscope with transillumination accomplished by placing a fiberoptic light (AdDent Inc, Danbury, CT) under the wing of the rubber dam clamp. In cases with a periradicular radiolucency, aqueous calcium hydroxide (Ultradent, South Jordan, UT) was placed as an intracanal medicament, the access cavity was temporized, and the patient returned for a second appointment 2 to 3 weeks later. To finalize endodontic treatment, the canals were dried and then obturated with Roth 801 sealer (Roth International, Chicago, IL) and gutta-percha. Obturation materials were then removed 2–3 mm apical to the deepest extent of the radicular crack. After conditioning (Caulk 34% Tooth Conditioner; Dentsply Caulk, Milford, DE) and applying a dental bonding agent (Prime & Bond NT, Dentsply Caulk), Giomer (Beautifil Flow Plus; Shofu Inc, Kyoto, Japan), a fluoride-releasing resin with prereacted nanoglass particles, was placed as an extended orifice barrier (Fig. 1*A* and *B*). The same materials were used to place orifice barriers (2–3 mm) in all other canals and to line the pulpal floor. A chlorhexidine-soaked cotton pellet and glass ionomer (Fuji IX; GC America, Alsip, IL) were placed as temporary filling materials.

Postoperative Protocol

After endodontic treatment, the tooth was reduced out of occlusion with all excursive contact eliminated. If an existing full-coverage restoration was present, it was checked and adjusted into light occlusion with no excursive interferences.

Patients were instructed to return to their dentist as soon as possible for placement of a crown. For those teeth with existing full-coverage restorations, a permanent core filling material was acceptable. Patients were cautioned to maintain a soft diet and completely avoid chewing on the side of the affected tooth until the final restoration was placed.

A follow-up appointment was made 6 weeks postendodontic treatment to verify that the final restoration was placed and to adjust for occlusal discrepancies or hyperocclusion. Further recall appointments were performed at 6 months, 1 year, and 2 to 4 years postoperatively. At those appointments, subjective patient feedback data were gathered, occlusion was checked and adjusted if needed, and periodontal probing depths were recorded. In addition to clinical evaluation (percussion, palpation, and examination for signs of infection), periapical radiographs were made at recall appointments to assess periradicular health and any changes in the periodontium.

Outcome Measures

To be included in this study, patients had to present for follow-up at a minimum of 2 years after endodontic treatment. The category of "success" was given to a case if the following criteria were met:

1. the patient was asymptomatic (ie, the patient had no symptoms affecting function or indicative of disease);
2. there were no clinical signs of infection (ie, sinus tract, swelling, purulence, etc);
3. there was no sensitivity to percussion, palpation, or biting pressure on a cotton roll;
4. the tooth was restored with a crown and in occlusal function;
5. periodontal probing depths were not increased $>$1 mm from initial measurements;
6. no increasing crestal alveolar bone loss was noted radiographically; and
7. normal-appearing periradicular structures were apparent with a periapical index (PAI) score $\leq$2.

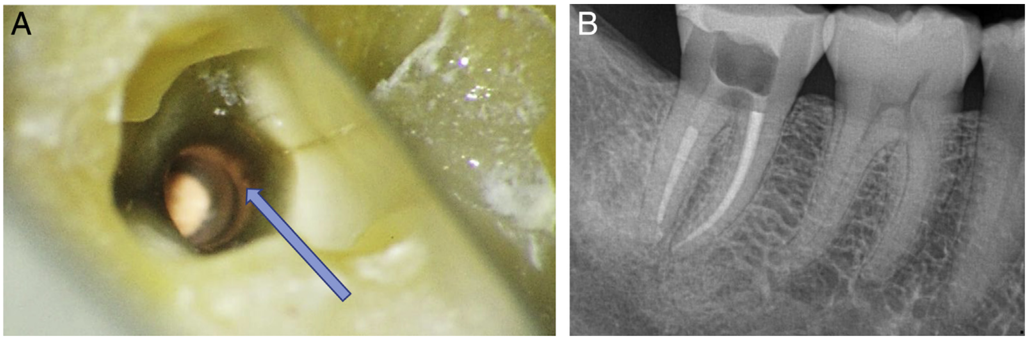

FIGURE 1 – (*A*) A microscopic view internally of a radicular crack extending 3 mm beyond the level of the canal orifice (*arrow*) and (*B*) an intraorifice barrier placed 2–3 mm apical to the internal extent of the crack in the distal canal.

PAI, first described by Ørstavik et al[16], was used to evaluate the presence of periapical periodontitis (Table 1) and has been 1 of the standard metrics used in endodontic outcomes studies[17–20]. Immediate postoperative and 2- to 4-year follow-up digital periapical radiographs were evaluated and scored independently by 2 experienced, board-certified endodontists. Radiographs were randomized and included 12 control radiographs to calibrate interrater agreement.

An outcome of "healing/uncertain" was assigned to those cases in which the success criteria were met with the following exception: the PAI score had improved, but a final score of ≤2 was not agreed on by the raters. "Failure" was assigned at 2 to 4 years if the final PAI score ranged from 3 to 5, if new or persistent symptoms indicative of disease were present, or if the tooth was extracted. A tooth was considered "survived" if it was present, asymptomatic, and functional. All statistical analyses were performed using R-3.3.4 (R Foundation, Vienna, Austria; http://www.r-project.org).

RESULTS

Seventy teeth in 69 patients, which comprised 8.4% of all completed nonsurgical endodontic cases by a single practitioner in private practice over 1 year, were enrolled in the study. Table 2 shows preoperative and intraoperative data within the study population. Study exclusions were 2 patients who died and 3 others who neglected to follow the postoperative protocol of restoring the tooth and returned months later with a split or nonrestorable tooth. This left 65 teeth available for analysis over the 2- to 4-year study. Six patients were lost to follow-up. Another 6 patients refused or were unable to present for recall but were contacted, along with their general dentists, to confirm the presence of the restored tooth and the absence of symptoms. These teeth were included in the survival analysis (n = 59) but were excluded from the success calculations. Success analysis was based on 53 teeth in 52 patients who presented for the 2- to 4-year follow-up (mean = 2.8 years, range = 2.1–4.1 years), yielding an 81.5% recall rate.

TABLE 1 - Periapical Index (PAI) for Radiographic Scoring[20]

PAI Score	Description
1	Normal periapical structures
2	Small changes in bone structure
3	Changes in bone structure with some mineral loss
4	Periodontitis with well-defined radiolucent area
5	Severe periodontitis with exacerbating features

Our pretreatment data (Table 2) were similar to other cracked tooth studies[2–5,11–13,21,22]. The average age of a patient in our cohort was 56.2 years (range = 16–91 years), which exceeded the average age of the population of our geographic area by approximately 11 years. Mandibular second molars (32.9%) and maxillary first molars (31.4%) were by far the most commonly cracked tooth followed by mandibular first molars (18.6%), maxillary second molars (10%), maxillary first premolars (4.3%), and maxillary and mandibular second premolars (1.4% each). A total of 127 cracks radiating from the endodontic access cavity (or center point of the occlusal surface) were identified, and 62.8% of cases had more than 1 crack. As expected, the majority of teeth had cracks with a mesiodistal orientation and marginal ridge involvement (94.3%), with most of the cases involving both marginal ridges (58.6%).

The average depth of the deepest internal cracks was 2.98 mm measured from the level of the canal orifice; 21.4% had an isolated pretreatment pocket depth greater than 4 mm (ranging from 5–7 mm) corresponding with the location of the radicular crack. Forty percent had a preoperative diagnosis of irreversible pulpitis, 51.4% had a diagnosis of pulpal necrosis, and 8.6% were previously endodontically initiated or treated. 42.9% had a pretreatment apical radiolucency, 72.9% had a diagnosis of periapical periodontitis (asymptomatic apical periodontitis, symptomatic apical periodontitis, acute apical abscess, or chronic apical abscess), and 42.9% were terminal teeth in the arch.

After endodontic treatment, the mean time it took for patients to return to their dentist for the final restoration was 25.4 days, and restorations were complete at 47.8 days. At our recall visits, 78.7% of patients required occlusal adjustment of the final coronal restoration because of hyperocclusion.

For the 2 independent endodontists interpreting the radiographs, an intraclass correlation coefficient for interrater agreement of PAI scores had a calculated kappa value of 0.87, equating to Landis and Koch's "almost perfect agreement"[23]. There was an overall mean PAI reduction of 1.16 over the study period, and those with pretreatment apical periodontitis (PAI ≥3) had a mean reduction of 2.14.

There was a 100% survival rate in the first 2 years and 96.6% survival up to the 4-year period. Using the aforementioned strict criteria, 48 of 53 teeth, or 90.6%, were classified as "success" in the 2- to 4-year term. In relation to success, statistical significance was not achieved by any of the pretreatment variables: marginal ridge involvement, pulpal and periapical diagnosis, presence of a lesion, pretreatment pocketing, crack depths into the canal, and terminal tooth position in the arch (Table 3).

TABLE 2 - Pretreatment and Treatment Data

Variable	Parameter/description	*n* (%)
Age (y)	<25	1 (1.4)
	25–34	3 (4.3)
	35–44	5 (7.1)
	45–54	21 (30)
	55–64	24 (34.3)
	>64	16 (22.9)
	Mean	56.2
	Median	56
	Range	16–91
Sex	Male	32 (45.7)
	Female	38 (54.3)
Tooth type	Mandibular 2nd molar	23 (32.9)
	Mandibular 1st molar	13 (18.6)
	Mandibular 2nd premolar	1 (1.4)
	Mandibular 1st premolar	0 (0)
	Maxillary 2nd molar	7 (10.0)
	Maxillary 1st molar	22 (31.4)
	Maxillary 2nd premolar	1 (1.4)
	Maxillary 1st premolar	3 (4.3)
Arch	Mandibular	37 (52.9)
	Maxillary	33 (47.1)
Tooth position	Terminal tooth in the arch	30 (42.9)
Number of cracks radiating from the endodontic access cavity	Total number	127
	1	26 (37.1)
	2	42 (60.0)
	3	1 (1.4)
	4	1 (1.4)
Surface location of crack(s)	Mesial	45 (35.4)
	Distal	65 (51.2)
	Facial	7 (5.5)
	Lingual	10 (7.9)
Marginal ridge involvement	Neither	4 (5.7)
	At least one	66 (94.3)
	Mesial marginal ridge (MMR) only	3 (4.3)
	Distal marginal ridge (DMR) only	22 (31.4)
	Both MMR and DMR	41 (58.6)
Existing restorations	None	3 (4.3)
	Occlusal amalgam	15 (21.4)
	Occlusal composite	8 (11.4)
	2-surface amalgam	10 (14.2)
	2-surface composite	8 (11.4)
	3, 4, and 5-surface amalgam	7 (10.0)
	3, 4, and 5-surface composite	6 (8.6)
	Crown	13 (18.6)
Depth of cracks internally from the level of the canal orifice	Mean depth (range = 0–5 mm)	2.98 mm
Pretreatment pocket	Depth ≥5 mm (range 5–7 mm)	15 (21.4)
Pretreatment pulpal diagnosis	Asymptomatic irreversible pulpitis	3 (4.3)
	Symptomatic irreversible pulpitis	25 (35.7)
	Pulpal necrosis	36 (51.4)
	Previously initiated treatment	3 (4.3)
	Previously treated	3 (4.3)
Pretreatment periapical diagnosis	Normal	19 (27.1)
	Asymptomatic apical periodontitis	4 (5.7)
	Symptomatic apical periodontitis	36 (51.4)
	Acute apical abscess	10 (14.3)
	Chronic apical abscess	1 (1.4)
Pretreatment lesion present	Yes	30 (42.9)
	No	40 (57.1)
Tooth in function	Tooth has an opposing tooth (functional, and in occlusion)	70 (100)

TABLE 3 - Prognosis (Success) of Cracked Teeth with Radicular Extensions

Variable	*n* (% of total)	Success (%)	Nonsuccess (%) (failure, uncertain, healing)	*P*-value (Fisher exact test)
Crack depth from canal orifice				.1917
0–2 mm	26 (49.1)	22 (84.6)	4 (15.4)	
3–5 mm	27 (50.9)	26 (96.3)	1 (3.7)	
Marginal ridge involvement				.0684*
Neither	4 (7.5)	4 (100)	0 (0)	
MMR only	3 (5.7)	3 (100)	0 (0)	
DMR only	15 (28.3)	15 (100)	0 (0)	
Both	31 (58.5)	26 (83.9)	5 (16.1)	
Probing depth				.3154
<5 mm	41 (77.4)	38 (92.7)	3 (7.3)	
5–7 mm	12 (22.6)	10 (83.3)	2 (16.7)	
Pretreatment pulpal diagnosis				.3756
Pulpitis (AIP, SIP)	21 (42.9)	20 (95.2)	1 (4.8)	
Pulp necrosis	28 (57.1)	24 (85.7)	4 (14.3)	
Pretreatment periradicular diagnosis				1.000
Normal	12 (22.6)	11 (91.7)	1 (8.3)	
AAP, SAP, AAA, CAA	41 (77.4)	37 (90.2)	4 (9.8)	
Pretreatment periapical lesion radiographically				1.000
No Lesion	29 (54.7)	26 (89.7)	3 (10.3)	
Lesion	24 (42.1)	22 (91.7)	2 (8.3)	
Terminal tooth				.6486
No	29 (54.7)	27 (93.1)	2 (6.9)	
Yes	24 (45.3)	21 (87.5)	3 (12.5)	

AAA, acute apical abscess; AAP, asymptomatic apical periodontitis; AIP, asymptomatic irreversible pulpitis; CAA, chronic apical abscess; DMR, distal marginal ridge; MMR, mesial marginal ridge; SAP, symptomatic apical periodontitis; SIP, symptomatic irreversible pulpitis.
*"Both" versus all others combined ("MMR only" + "DMR only" + "neither").

DISCUSSION

This study is the first to prospectively look at the success and survival of endodontically treated, cracked teeth with radicular extensions. The validity of the current study was likely increased because of 2 factors: study design and treatment methodology. A prospective cohort reduces potential sources of bias and confounding variables. Another advantage to the prospective design was our ability to obtain a recall rate of 81.5%, which exceeds that of most endodontic outcome studies. Also, the 2- to 4-year patient recall allowed adequate time for endodontic healing to take place[24].

All endodontic treatment was performed by a single endodontist in private practice using microscopy and modern techniques, all of which maximize standardization and relevance. Of special note was the use of intraorifice barriers placed beyond the extent of the fracture. Intraorifice barriers have become a part of modern endodontic technique, providing a superior coronal seal to gutta-percha[25] and potentially improving fracture resistance[26]. Also, it has been shown that bacterial biofilms are likely ubiquitous in tooth fractures[27]; thus, an intraorifice barrier may have particular importance for radicular cracks because the crown margin will not cover the full extent of the crack.

Because of the increased vulnerability of the endodontically treated cracked tooth before the coronal restoration, a specific postoperative protocol was used after endodontic treatment to mitigate the risk of further crack propagation. In addition to complete occlusal reduction, patients were told to avoid chewing on the side of the affected tooth and to return to their dentist as soon as possible for the final full-coverage restoration.

The importance of the coronal restoration to the survival of endodontic treatment cases has been shown[28]. One systematic review of the literature calculated an odds ratio for those endodontically treated teeth that did not receive a crown, finding they were 4 times less likely to survive than those restored with full crowns[29]. For cracked teeth, full-coverage restorations and avoidance of post placement likely minimize further crack propagation apically and associated periodontal destruction[3,30]. Our data showed that after crown placement, 98.1% of the study population displayed no increase in probing depths over time.

Emphasis was given to patients on the importance of follow-up appointments. One noteworthy posttreatment observation was that 78.7% of patients presenting at follow-up required occlusal adjustment of their final restoration. This is significant because of the likelihood that masticatory forces, parafunctional stresses, and malocclusion are etiologic factors that initiate and induce apical propagation of the crack[2,30]. For this reason, a 6-week follow-up verifying the presence of the final restoration and checking and adjusting occlusion was implemented in our study. It is also important that restorative dentists be informed of the particular importance of occlusion in these cases.

Our survival rate of 96.6% is comparable with outcomes stated in the literature, as endodontically treated cracked teeth have a range from 85.5%–96.8% with 2+ years follow-up[11–13]. The same studies found a reduced survival for those teeth with subgingival or radicular extensions of the crack ranging from 66.7%–88.3% at 2 to 5 years. Our higher survival rate in this population may be due to our technique of placing orifice barriers apical to the crack, the requirement of crown placement, and our strict postoperative protocol.

Two teeth (3.4%) were deemed failures: 1 at 3.2 years and another at 2.4 years posttreatment. In the first case, pain and swelling were present, deep pocketing with purulent exudate was noted, significant crestal and furcal bone loss was observed radiographically, and a crack across the pulpal floor was observed upon access into the crown. This marked the only true failure at the level of the fracture. In the second case, despite radiographic and clinical assessment showing no signs of pathosis, the patient insisted on extracting the tooth because of persistent symptoms.

Three cases (5.7%) in our study were deemed "healing/uncertain" because the interrater agreement could not be reached on whether the 2- to 4-year follow-up radiograph scored PAI $\leq$2. All 3 of these teeth were asymptomatic and functional, but because of our parameters for success, they could not be categorized as such. Two teeth required endodontic retreatments before the 2- to 4-year recall: the first because of failure of the coronal restoration (leakage) and the second because of an untreated, missed canal with periradicular disease. Both were reentered into the study and deemed successful after an additional 2+ years postretreatment.

A success rate of 90.6% is higher than outcomes reported in the literature for cracked teeth. Krell and Caplan[5] found an 82% overall success rate in 380 endodontically treated cracked teeth at the 1-year follow-up. They noted a reduced prognosis with distal marginal ridge involvement and an even lower prognosis when both distal and mesial marginal ridges were involved. The present study showed no obvious reduction in success with a single marginal ridge fracture, but a similar reduced success rate was observed for those teeth with cracks involving both mesial and distal marginal ridges (83.9% success) although this was not statistically significant. We also found a 92.7% success rate when probing depths were 4 mm or less and 83.8% when probings were 5–7 mm, although this too did not show statistical significance. In contrast, Krell and Caplan found a 41% success rate for those cracked teeth with periodontal probing depths $\geq$5mm. The higher success rate in periodontally involved cases in the present study may reflect our range of 5–7 mm versus their range of all depths 5 mm or greater, which likely included more catastrophic fractures. Their study also found periapical diagnosis to be a significant predictor of success, whereas the present analysis found no significance with the pretreatment periradicular diagnosis or presence of a lesion (Table 3).

Interestingly, the success (90.6%) and survival rates (96.6%) of the present study are comparable with studies looking at nonsurgical endodontically treated teeth in general, which show survival rates from 86.4%–98.1%[29,31] and success rates ranging from 82.1%–92.9%[17,19,32] over similar time periods. Therefore, our study suggests that cracked teeth, even those with radicular extensions, may have similar success and survival to noncracked teeth after endodontic treatment if certain protocols are used. Further long-term, prospective studies are necessary to confirm our findings.

Particularly challenging in this cohort is that outcomes had to be assessed both endodontically and periodontally. Cracked teeth with radicular extensions are unique in that periodontal "success" must likely be measured, not by resolution of pocketing but by minimal to no change ($\pm$1 mm) in recorded depths or radiographic crestal bone loss. Considering the potential for persistent pocketing, a periodontal referral may be necessary in these cases; 21.4% of our original study population presented with pretreatment pocketing ranging from 5–7 mm adjacent to the crack. During the 4-year observation period, only 2 of these cases had an increase in probing depth and each by just 1 mm, whereas most cases remained unchanged or had slight improvements. Over the study period, there was an overall average of 0.41-mm probing depth reduction, or improvement, at the site of the radicular crack(s). Although this change could indicate healing, it may also represent the normal generalized periodontal recession that occurs over time in adults[33], whereas the periodontal defect at the site of the crack remains static. Other explanations could be the variability intrinsic to repeated probing measurements and restricted access to probing interproximally. These challenges could account for a lower percentage of teeth documented as having preoperative probing depths adjacent to the crack, thus rendering our numbers a conservative estimate.

Digital periapical radiography was used in preference to cone-beam computed tomographic (CBCT) imaging for multiple reasons. First, our purpose was to make statements on the success and survival of cracked teeth with radicular extensions and to compare our outcomes with existing studies, which have largely used periapical radiography with PAI[17–20]. Second, an American Association of Endodontists and American Academy of Oral and Maxillofacial Radiology joint position paper states that routine use of CBCT imaging is discouraged for endodontic diagnosis or screening purposes[34], which is within the ethical recommendation of the "as low as reasonably achievable" principle for radiography. Third, recent studies have shown that the periodontal ligament space of a healthy tooth displays significant variation when examined by CBCT imaging, resulting in a higher risk of misdiagnosis and overtreatment[35,36]. This risk of overdiagnosis, or falsely identifying disease where none exists, has been found to be higher in root-filled teeth[35]. Further investigations are needed before CBCT imaging can be used predictably for outcome or epidemiologic studies[36].

A major limitation of this study is the small sample size resulting in potentially inadequate numbers for meaningful statistical analyses. For this reason, this study should be classified as a pilot study. More prospective studies with longer follow-up times and larger sample sizes would be beneficial to assess the longer-term ramifications of the presence of radicular cracks and to elucidate whether the measured variables truly have an impact on success.

CONCLUSION

Data on our 2- to 4-year prospective cohort indicates a 90.6% success and 96.6% survival rate for cracked teeth with radicular extensions. These are comparable outcomes with those reported in the literature for endodontically treated teeth in general over similar lengths of time. These cracked teeth with radicular extensions have historically been deemed "hopeless" or "nonrestorable" without evidence. However, using specific treatment and posttreatment protocols in this subset of teeth may result in greater longevity and a higher success than has been thought previously. Modern endodontic techniques, including microscope-assisted intraorifice barriers placed apical to the level of the crack, complete occlusal reduction of the tooth postendodontically, and expeditious placement of a full-coverage restoration with proper occlusal equilibration, may be factors that account for a better outcome.

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REFERENCES

1. Rivera E, Walton ER. Cracking the cracked tooth code: detection and treatment of various longitudinal tooth fractures. Endod Colleagues Excell 2008; Summer: 2–7.
2. Hiatt WH. Incomplete crown-root fracture in pulpal-periodontal disease. J Periodontol 1973;44:369–79.
3. Krell KV, Rivera EM. A six year evaluation of cracked teeth diagnosed with reversible pulpitis: treatment and prognosis. J Endod 2007;33:1405–7.
4. Abbott P, Leow N. Predictable management of cracked teeth with reversible pulpitis. Aust Dent J 2009;54:306–15.
5. Krell KV, Caplan DJ. 12-month success of cracked teeth treated with orthograde root canal treatment. J Endod 2018;44:543–8.
6. Tsesis I, Rosen EI, Tamse A, et al. Diagnosis of vertical root fractures in endodontically treated teeth based on clinical and radiographic indices: a systematic review. J Endod 2010;36:1455–8.
7. Alkhalifah S, Alkandari H, Sharma PN, Moule AJ. Treatment of cracked teeth. J Endod 2017;43:1579–86.
8. Ailor JE. Managing incomplete tooth fractures. J Am Dent Assoc 2000;131:1168–74.
9. Khaler W. The cracked tooth conundrum: terminology, classification, diagnosis, and management. Am J Dent 2008;21:275–82.
10. Dugas NN, Lawrence HP, Teplitsky P, Friedman S. Quality of life and satisfaction outcomes of endodontic treatment. J Endod 2002;28:819–27.
11. Tan L, Chen NN, Poon CY, Wong HB. Survival of root filled cracked teeth in a tertiary institution. Int Endod J 2006;39:886–9.
12. Sim IG, Lim TS, Krishnaswamy G, Chen NN. Decision making for retention of endodontically treated posterior cracked teeth: a 5-year follow-up study. J Endod 2016;42:225–9.
13. Kang SH, Kim BS, Kim Y. Cracked teeth: distribution, characteristics, and survival after root canal treatment. J Endod 2016;42:557–62.
14. STROBE statement–checklist of items that should be included in reports of observational studies (STROBE Initiative). Int J Public Health 2008;53:3–4.
15. Friedman S, Azarpazhooh A, Bruder GA, et al. Guidelines for the methodology of cracked tooth studies. American Association of Endodontists. Available at: www.aae.org; 2016. Accessed March 3, 2019.
16. Orstavik D, Kerekes K, Eriksen HM. The periapical index: a scoring system for radiographic assessment of apical periodontitis. Endod Dent Traumatol 1986;2:20–34.
17. Doyle SL, Hodges JS, Pesun IJ, et al. Retrospective cross sectional comparison of initial nonsurgical endodontic treatment and single-tooth implants. J Endod 2006;32:822–7.
18. Penesis VA, Fitzgerald PI, Fayad MI, et al. Outcome of one-visit and two-visit endodontic treatment of necrotic teeth with apical periodontitis: a randomized controlled trial with one-year evaluation. J Endod 2008;34:251–7.
19. Paredes-Vieyra J, Enriquez FJ. Success rate of single-versus two-visit root canal treatment of teeth with apical periodontitis: a randomized controlled trial. J Endod 2012;38:1164–9.
20. Huumonen S, Lenander-Lumikari M, Sigurdsson A, Ørstavik D. Healing of apical periodontitis after endodontic treatment: a comparison between a silicone-based and a zinc oxide-eugenol-based sealer. Int Endod J 2003;36:296–301.
21. Seo DG, Yi YA, Shin SJ, Park JW. Analysis of factors associated with cracked teeth. J Endod 2012;38:288–92.
22. Kim SY, Kim SH, Cho SB, et al. Different treatment protocols for different pulpal and periapical diagnoses of 72 cracked teeth. J Endod 2013;39:449–52.
23. Landis JR, Koch GG. An application of hierarchical kappa-type statistics in the assessment of majority agreement among multiple observers. Biometrics 1977;33:363.
24. Ørstavik D. Time-course and risk analyses of the development and healing of chronic apical periodontitis in man. Int Endod J 1996;29:150–5.
25. Pisano DM, DiFiore PM, McClanahan SB, et al. Intraorifice sealing of gutta-percha obturated root canals to prevent coronal microleakage. J Endod 1998;24:659–62.

26. Nagas E, Uyanik O, Altundasar E, et al. Effect of different intraorifice barriers on the fracture resistance of roots obturated with resilon or gutta-percha. J Endod 2010;36:1061–3.

27. Ricucci D, Siqueira JF, Loghin S, Berman LH. The cracked tooth: histopathologic and histobacteriologic aspects. J Endod 2015;41:343–52.

28. Ray HA, Trope M. Periapical status of endodontically treated teeth in relation to the technical quality of the root filling and the coronal restoration. Int Endod J 1995;28:12–8.

29. Ng YL, Mann V, Gulabivala K. Tooth survival following non-surgical root canal treatment: a systematic review of the literature. Int Endod J 2010;43:171–89.

30. Gutmann JL, Rakusin H. Endodontic and restorative management of incompletely fractured molar teeth. Int Endod J 1994;27:343–8.

31. Alley BS, Kitchens GG, Alley LW, Eleazer PD. A comparison of survival of teeth following endodontic treatment performed by general dentists or by specialists. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2004;98:115–8.

32. Ng YL, Mann V, Rahbaran S, et al. Outcome of primary root canal treatment: systematic review of the literature - part 1. Effects of study characteristics on probability of success. Int Endod J 2007;40:921–39.

33. Albandar JM, Kingman A. Gingival recession, gingival bleeding, and dental calculus in adults 30 years of age and older in the United States, 1988-1994. J Periodontol 1999;70:30–43.

34. Fayad MI, Nair M, Levin MD, et al. AAE and AAOMR Joint Position Statement: use of cone beam computed tomography in endodontics 2015 update. Oral Surg Oral Med Oral Pathol Oral Radiol 2015;120:508–12.

35. Kruse C, Spin-Neto R, Evar Kraft DC, et al. Diagnostic accuracy of cone beam computed tomography used for assessment of apical periodontitis: an ex vivo histopathological study on human cadavers. Int Endod J 2018;52:1–12.

36. Pope O, Sathorn C, Parashos P. A comparative investigation of cone-beam computed tomography and periapical radiography in the diagnosis of a healthy periapex. J Endod 2014;40:360–5.