

Distribution Statement

Distribution A: Public Release.

The views presented here are those of the author and are not to be construed as official or reflecting the views of the Uniformed Services University of the Health Sciences, the Department of Defense or the U.S. Government.



UNIFORMED SERVICES UNIVERSITY OF THE HEALTH SCIENCES

POSTGRADUATE DENTAL COLLEGE
NAVAL POSTGRADUATE DENTAL SCHOOL
8955 WOOD ROAD
BETHESDA, MARYLAND 20889



THESIS APPROVAL PAGE FOR MASTER OF SCIENCE IN ORAL BIOLOGY

Title of Thesis: Outcome of endodontically treated cracked teeth

Name of Candidate: Austin B. McIntyre
Master of Science Degree
April 14, 2023

THESIS/MANUSCRIPT APPROVED:

DATE:

OSBORNE.NANCY.1167256305 Digitally signed by
OSBORNE.NANCY.1167256305
Date: 2023.06.07 07:32:51 -04'00'

6/7/23

Nancy Osborne
ENDODONTICS DEPARTMENT
NAVAL POSTGRADUATE DENTAL SCHOOL
Committee Chairperson

HINMAN.SUSAN.ELIZABETH.1261278240 Digitally signed by
HINMAN.SUSAN.ELIZABETH.1261278240
Date: 2023.06.07 08:31:48 -04'00'

6/7/23

Susan E. Hinman
ENDODONTICS DEPARTMENT
NAVAL POSTGRADUATE DENTAL SCHOOL
Committee Member

IMAMURA.GLEN.MASAO.1088288510 Digitally signed by
IMAMURA.GLEN.MASAO.1088288510
DN: c=US, o=U.S. Government, ou=DoD, ou=PKI,
ou=OTHER,
cn=IMAMURA.GLEN.MASAO.1088288510
Date: 2023.06.07 16:03:31 -04'00'

6/7/23

Glen M. Imamura
RESEARCH DEPARTMENT
NAVAL POSTGRADUATE DENTAL SCHOOL
Committee Member

OUTCOME OF ENDODONTICALLY TREATED CRACKED TEETH

by

Austin Brett McIntyre
Lieutenant Commander, Dental Corps
United States Navy

A thesis submitted to the Faculty of the
Endodontics Graduate Program
Naval Postgraduate Dental School
Uniformed Services University of the Health Sciences
In partial fulfillment of the requirements for the degree of
Master of Science
in Oral Biology
June 2023

THESIS APPROVAL PAGE
INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

This interim analysis owes its accomplishment to the invaluable support of numerous Endodontic Residents, who diligently enrolled and tracked patients, and the ongoing mentorship and guidance provided by the esteemed Endodontic and Research Staff.

DISCLAIMER

The views presented here are those of the author and are not to be construed as official or reflecting the views of the Uniformed Services University of the Health Sciences, the Department of Defense or the U.S. Government.

ABSTRACT

Outcome of Endodontically Treated Cracked Teeth

Austin Brett McIntyre, D.D.S., 2023

Thesis directed by: CAPT Nancy Osborne, D.D.S., M.S.
Department Chair
Endodontics Department
Naval Postgraduate Dental School

Introduction: The growing prevalence of cracked teeth among the general population often pose diagnostic challenges for dental providers, as visualization of cracks and reproduction of their symptoms can be challenging. Cracked teeth commonly exhibit temperature sensitivity and sharp pain upon biting. If left untreated, cracks will be colonized by bacteria and possibly propagate; further jeopardizing the pulpal and/or periapical tissues. If signs and symptoms of symptomatic irreversible pulpitis, pulp necrosis, or periapical disease are observed, non-surgical root canal treatment (NSRCT) is indicated. However, there are limited studies that address the long-term outcome of endodontically treated cracked teeth. **Objectives:** To evaluate the five-year outcomes of endodontically treated cracked teeth that included a 5-year survivability analysis. A secondary aim was to identify any variables that influenced those outcomes. **Methods:** Subjects with cracked teeth requiring initial NSRCT were identified by Naval Postgraduate Dental School (NPDS) endodontic residents. Subjects received NSRCT and were scheduled for annual follow-up visits over a five-year period. During each visit, standardized forms were used to collect radiographic and clinical data, which were then analyzed to determine the endodontic outcome. Outcomes were defined as “Survived” (present at recall), “Functional” (asymptomatic and present) and “Healed” (functional, a periapical index score (PAI) of 1 or 2 and no probing depths changes > 1mm). **Results:** This interim analysis of 166 subjects (n=167 teeth) indicated that at

one year, 65% were healed and 79% were functional. The only variable identified that decreased prognosis was the present of an intracanal post ($p=0.019$). A survivability analysis determined that the estimated survival to 5 years was 79% (95% CI 71%-89%). **Conclusions:** This current study provides evidence to suggest that initial endodontic treatment is a reliable approach for treating cracked teeth, with predictable and favorable outcomes.

TABLE OF CONTENTS

LIST OF TABLES	Error! Bookmark not defined.
LIST OF FIGURES	Error! Bookmark not defined.
LIST OF ABBREVIATIONS	Error! Bookmark not defined.
CHAPTER 1: Introduction	1
CHAPTER 2: Materials and Methods	5
CHAPTER 3: Results	8
Study Demographics and Crack Incidence	8
Survival Analysis	8
Healed and Functional Analysis	9
Variables	9
CHAPTER 4: Discussion.....	15
CHAPTER 5: Conclusions	19
APPENDIX A Cracked Tooth Data Form.....	20
APPENDIX B Cracked Tooth Pre-Operative Data Form.....	21
APPENDIX C Cracked Tooth Access Data Form.....	22
APPENDIX D Registry/Cracked Tooth Pre-Operative Data Form.....	23
APPENDIX E Registry/Cracked Tooth Intra-Operative Data Form.....	24
APPENDIX F Registry/Cracked Tooth Follow-Up Data Form	25
REFERENCES	26

LIST OF TABLES

Table 1. The incidence of a crack for a particular tooth type expressed as a percentage, and the number of subjects	10
Table 2. Characteristics by functional status at follow-up year 1.	13
Table 3. Characteristics by healed status at follow-up year 1	14

LIST OF FIGURES

Figure 1. Survival Analysis.....	11
Figure 2. Healed and Functional Analysis	12

LIST OF ABBREVIATIONS

AAE	American Association of Endodontists
CBCT	Cone Beam Computed Topography
CI	Confidence Interval
NPDS	Naval Postgraduate Dental School
NSRCT	Non-Surgical Root Canal Treatment
PAI	Periapical Index
PA	Periapical
PARL	Periapical Radiolucency

CHAPTER 1: Introduction

As defined by the American Association of Endodontists (AAE), a cracked tooth is characterized by “a thin surface disruption of enamel and dentin, and possibly cementum, of unknown depth or extension”¹. In recent years, the incidence of cracked teeth has become an increasingly challenging and widespread issue in the field of dentistry. Amidst the Covid-19 pandemic, there was a notable rise in the occurrence of cracked teeth, particularly among males between the ages of 40 to 60². Despite the reported rise in occurrence in recent years; cracked teeth are not a modern phenomenon.

In 1954, Gibbs authored the initial article on the subject, which introduced the phrase “cuspal fracture odontalgia” for patients presenting with pain on mastication, but otherwise unremarkable clinical and radiographic findings³. A decade after Gibbs’ publication, Cameron observed several recurring patterns in patients diagnosed with cracked teeth, including both pain when biting and unexplained sensitivity to temperature⁴. Cameron built on Gibbs’ work and introduced the more commonly used term “cracked tooth syndrome”. This term refers to “an incomplete fracture of a vital posterior tooth that affects dentin and occasionally extends to the pulp”⁴. This early research on cracked teeth helped establish a foundation for subsequent studies on the diagnosis and treatment of this common dental presentation.

Patients with cracked teeth can exhibit a variety of symptoms that often pose diagnostic and restorative challenges. The most commonly reported symptoms are increased sensitivity to thermal changes and sudden sharp pain upon initiation and release of occlusal forces⁵, with the mandibular second molar being the most frequently affected tooth⁴. This pain upon mastication may be attributed to the sudden movement of fluid in dentinal tubules as fractured segments of

the tooth move independently of each other⁶, which may prove difficult to reproduce for accurate diagnosis.

To overcome these diagnostic challenges, providers often rely on radiographic examination to aide in crack detection. However, a radiographic diagnosis of a crack is often unattainable, as cracks typically occur in a mesiodistal direction, parallel to the plane of the film^{7,8}. Cracks occurring in the buccolingual direction, however, are more easily visualized⁹. Teeth with vertical root fractures (VRF) can present with widened periodontal ligaments, J-shaped lesions, angular periodontal defects, or separated root fragments on periapical (PA) radiographs¹⁰.

With the increased accessibility of cone beam computed tomography (CBCT), providers may attempt to take advantage of improved resolution and accuracy compared to traditional 2-dimensional imaging. Although it is possible to evaluate and examine teeth and their surrounding structures with increased 3-dimensional accuracy, CBCT technology has proven unreliable in detecting cracks or fractures within the enamel or root structure¹¹. Cracks are typically too small to be detected on a scan, especially with the presence of metallic restorations and previously root filled teeth which produce artifacts and streaking, decreasing the specificity of CBCT images^{11,10,12}. Though unreliable in detecting specific enamel and radicular cracks, CBCT images can reveal early patterns of bone loss adjacent to the crack, such as a mesial or distal angular defect of interproximal bone and loss of cortical plate suggesting a vertical root fracture¹⁰. This demonstrates improved diagnostic potential for assessing the extent of cracks propagating within the radicular root structure and/or vertical root fracture^{10,13}.

Due to the limitations of radiographic evaluation, providers often rely on clinical symptoms for diagnosis. When a crack approaches the pulp, invasion of bacterial and their by-

products can cause pulpal inflammation, leading to increased temperature sensitivity characterized by reversible pulpitis and/or irreversible pulpitis¹⁴. Researchers observed that pulp necrosis and abscesses have been found in teeth that clinically appeared to be in good health with minimal restorations and no periodontal disease. Upon extraction and analysis, it was discovered that the cracks in the enamel and cementum enabled colonization of bacteria to infiltrate the pulp, thus leading to pulp necrosis and subsequent periapical pathology^{4,5,14,15,16}.

A cracked tooth does not necessarily have an unfavorable prognosis. Early diagnosis and treatment, particularly with full coverage restorations, can significantly improve a tooth's survival¹⁷. A common practice amongst providers is to perform non-surgical root canal treatment (NSRCT) on all cracked teeth exhibiting painful symptoms. However, a diagnosis of reversible pulpitis in teeth with cracks does not necessarily mandate definitive root canal treatment. Krell and Rivera's 2007 study demonstrated that only 21% of teeth diagnosed with reversible pulpitis progressed to irreversible pulpitis or pulpal necrosis requiring endodontic treatment¹⁸. More recently published research has also demonstrated that 71% of teeth diagnosed with crack and reversible pulpitis remained vital without symptoms of irreversible pulpitis or pulpal necrosis after three years of treatment with either orthodontic banding or cuspal coverage crowns¹⁴. Long term studies evaluating the prognosis of cracked teeth with root canal treatment are limited, however there is data to support root canal treatment as a viable option in retaining the patient's natural dentition. One-year outcomes of endodontically treated cracked teeth have demonstrated an 82% healed rate¹⁹, indicating radiographic signs of healing with no clinical signs and symptoms of pathosis.

In their 2007 publication, Krell and Rivera established three prognostic factors that significantly influenced the outcome of non-surgical root canal treatment on cracked teeth: the

depth of periodontal probing associated with the crack, the crack's location, and the pre-treatment diagnosis of periapical pathosis¹⁸. A tooth with a mesial marginal ridge crack and less than a 5mm probing depth, with no apical pathosis, had a 93% success rate. However, for teeth with distal marginal ridge cracks, the success rate dropped to 84%, and for those with apical pathosis, it decreased further to 69%. If the tooth exhibited a probing depth greater than 5mm on any marginal ridge crack, the success rate declined to 41%¹⁹.

Survival rates of cracked teeth have been reported in longer-term studies with rates of 97% at four years²⁰ and 92% at five years²¹. However, these studies do not provide information on the functional or healed status of the tooth beyond its presence in the mouth at the time of evaluation.

Despite the abundance of research on the diagnosis and treatment planning of cracked teeth, there is limited information on the long-term outcomes of cracked teeth that have had endodontic treatment. To date, only one survival study has been conducted evaluating NSRCT on cracked teeth over a period of five years^{21,22}, thus highlighting the critical need for more data on the long-term outcomes of such treatments. This information is essential to ensure that patients are fully informed and able to make autonomous decisions regarding their treatment plans.

Therefore, the aim of this combined retrospective and prospective study is to evaluate the five-year outcomes of endodontically treated cracked teeth, to include a 5-year survivability analysis. A secondary aim was to identify any variables that influenced those outcomes.

CHAPTER 2: Materials and Methods

This study, WRNMMC IRB #410603, “Outcome of Endodontically Treated Cracked Teeth”, is ongoing. The Material and Methods section for this paper was modified from the approved protocol.

STUDY DESIGN

This study consists of retrospective and prospective data collected from subjects referred to the endodontic clinic at the Naval Postgraduate Dental School (NPDS). Inclusion criteria for the study included the following: the subject 1) was at least 18 years of age; 2) willingly provided consent; 3) was diagnosed with a cracked tooth at the NPDS endodontic clinic; 4) required endodontic treatment on the cracked tooth; and 5) all endodontic treatment was performed by an NPDS endodontic resident or faculty member.

A thorough pre-operative radiographic and clinical examination was performed. Various methods were employed to aid in the diagnosis of a cracked tooth including direct visualization (with or without the use of magnification or a dental operating microscope), transillumination, methylene-blue dye application, and Tooth Slooth® bite test. For the prospective portion of the study, subjects were enrolled when a diagnosis of cracked tooth was made before the initiation of endodontic treatment, following the access preparation if a crack was noted or after completion of root canal therapy.

Data for the retrospective portion of this study was obtained from subjects consented and enrolled in a WRNMMC Institutional Review Board approved patient treatment registry maintained by the NPDS Endodontic Department. This registry collected information on subject demographics, health history, initial exam findings, perioperative notes, and follow-up data. Additional cracked tooth information was collected during the initial evaluation including tooth

characteristics, diagnostic methods, and fracture location. The data collection sheets the registry were identical to this study, and therefore facilitated subjects meeting study inclusion criteria.

Following the collection of pre-treatment data, NSRCT was provided. Subjects with previously initiated therapy from other clinics (i.e. pulpotomy or pulpectomy) were excluded from this study. No specified instrumentation technique, irrigation technique, or obturation technique was required, and all were documented on standardized data forms. Teeth were accessed using rubber dam isolation; information regarding crack location and extent was collected after access. Following completion of treatment and temporization, subjects were referred for the definitive restoration of the tooth. At a minimum of twelve months after the endodontic treatment, subjects returned for a follow-up clinical and radiographic examination. Each year following treatment, subjects were asked to return for subsequent follow-up examinations with data collection for up to five years.

Assessment of the clinical and radiographic data determined the outcome. The clinical examination included percussion, palpation, periodontal probing, mobility, and sensibility testing. The radiographic examination included one periapical radiograph at a minimum. Three calibrated, board-certified endodontists individually assessed the randomized immediate post-treatment and most recent follow-up radiographs on a shared laptop with image enhancement capabilities to establish a Periapical Index (PAI) score. A dichotomous classification system of healed or non-healed was used for each tooth. A tooth was considered healed if the following criteria were met: 1) the tooth was asymptomatic (absence of the following: pain, mobility, swelling, sinus tract, percussion sensitivity, change in probing depth greater than 1mm, and palpation sensitivity) and 2) the PAI score was 1 or 2. A tooth was considered non-healed if: 1) the tooth presented with symptoms 2) Probing depth changes at location of crack greater than

1mm or 3) the PAI score was 4, or 5. Teeth designated a PAI score of 3 were excluded from both the healed, and non-healed categories unless clinical symptoms were present, in which case the tooth was diagnosed as non-healed. In a separate analysis, all asymptomatic teeth, regardless of PAI score, were considered functional (clinical success) and all present (non-extracted) teeth regardless of symptoms were considered survived.

Although not initially incorporated into the original study protocol, survival probabilities were estimated over a five-year follow-up using the Kaplan-Meier method. This statistical approach takes into account the censoring of observations or incompletely observed survival times by calculating the probability of survival up to a specific time point as the product of conditional probabilities for intervals of available observation times. Separate analyses were carried out on evaluated teeth at each follow-up to determine the annual frequencies of healed and functional outcomes, accompanied by their respective 95% binomial confidence intervals.

Based on previously published literature, an expected healed rate of 70% with a desired 95% confidence interval of +/- 10% for the precision of the estimated healed rate produced the need for 93 subjects with 5 year follow ups for analysis. Those assumptions and a 5-year recall rate assumed at 45% were used to perform power analysis giving a target sample size of 250 subjects. Additionally, demographic and clinical characteristics were compared between the healed and functional groups at the 1-year follow-up using t-tests or Fisher's exact tests. The statistical analyses were performed using R software (Vienna, Austria)

CHAPTER 3: Results

This interim analysis includes both retrospective and prospective data. The retrospective study data is limited to the first 18 subjects that were enrolled in a WRNMMC Institutional Review Board approved Data Registry. This registry was closed in 2019. The remaining subjects were enrolled under the currently approved prospective study, WRNMMC IRB #410603, “Outcome of Endodontically Treated Cracked Teeth”. To date, 166 subjects (167 teeth) have been enrolled. Excluded from the analysis were 6 subjects categorized as “ineligible”, either due to improper enrollment or their voluntary withdrawal, resulting in a total of 161 teeth available for the extraction (survivability) analysis. Additionally, in the analysis for healed and functional rates, teeth that were not yet eligible for a follow-up appointment or had already been extracted were excluded from the analysis.

STUDY DEMOGRAPHICS AND CRACK INCIDENCE

The mean follow-up time was 2.3 years (SD 1.8 years). 73% were male and 27% were female with ages ranging from 21-83 years old with a mean age of 48 years. The most frequent tooth to exhibit a crack were mandibular second molars (38.5%) followed by the mandibular first molars (26.7%) (Table 1). The majority of cracked teeth were in a non-terminal position (54.7%) when compared to a terminal position (45.3%).

SURVIVAL ANALYSIS (Figure 1.)

If a tooth was present at recall it was considered survived despite clinical or radiographic signs or symptoms. The cumulative 5-year survival, or the estimated survival to 5 years for a member of the studied population, was 79% (95% CI 73-91%). The blue shaded area is the confidence interval and expands as it gets closer to five years. The “Number at risk” indicates subjects whose data was available at a given time point.

HEALED AND FUNCTIONAL ANALYSIS (Figure 2.)

One hundred fourteen subjects completed a one-year recall (81% recall rate), 77 completed a two-year recall (65% recall rate), 58 completed a three-year recall (51% recall rate), 38 completed a four-year recall (50% recall rate), and 23 completed a five-year recall (37% recall rate).

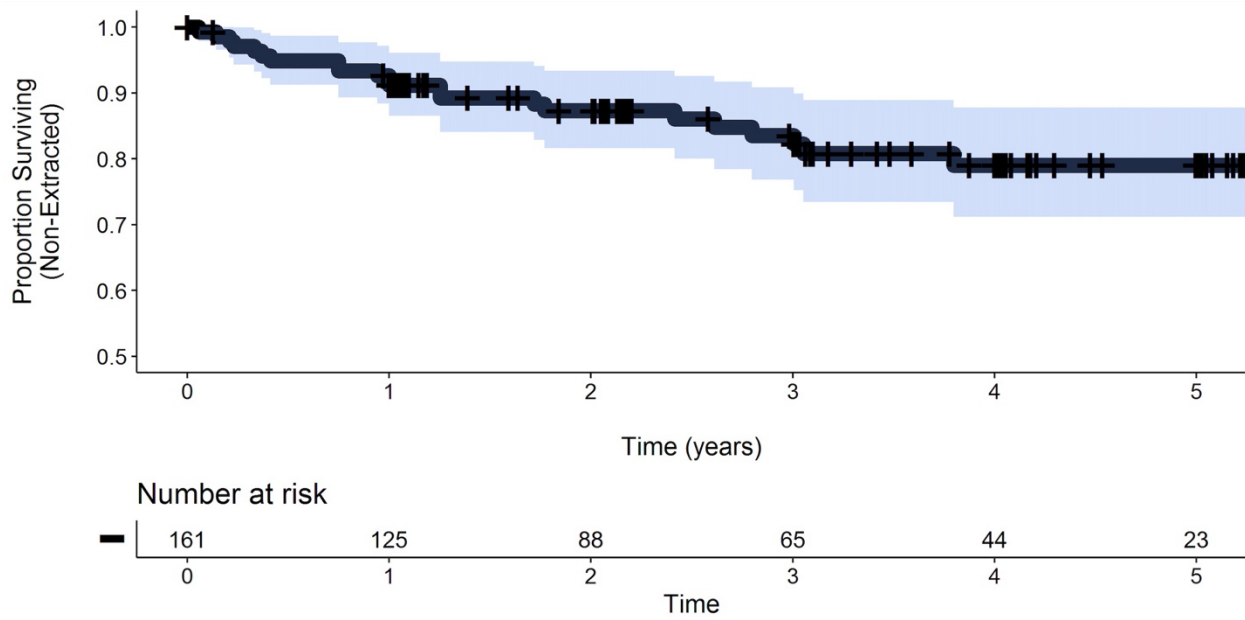
At one-year, 79% of teeth were functional (95%, CI 72%-85%) and 65% of teeth were healed (95%, CI 56%-73%) (Fig.1). The functional and healed rates for two years through five are: 86%(95% CI 76%-92%), 65%(95% CI 54%-75%)(two-year); 88%(95% CI 77%-94%), 67%(95% CI 54%-78%)(three-year); 92%(95% CI 78%-98%), 79%(95% CI 63%-89%)(four-year); and 87%(95% CI 67%-96%), 78%(95% CI 58%-91%)(five-year).

VARIABLES (Tables 2. & 3.)

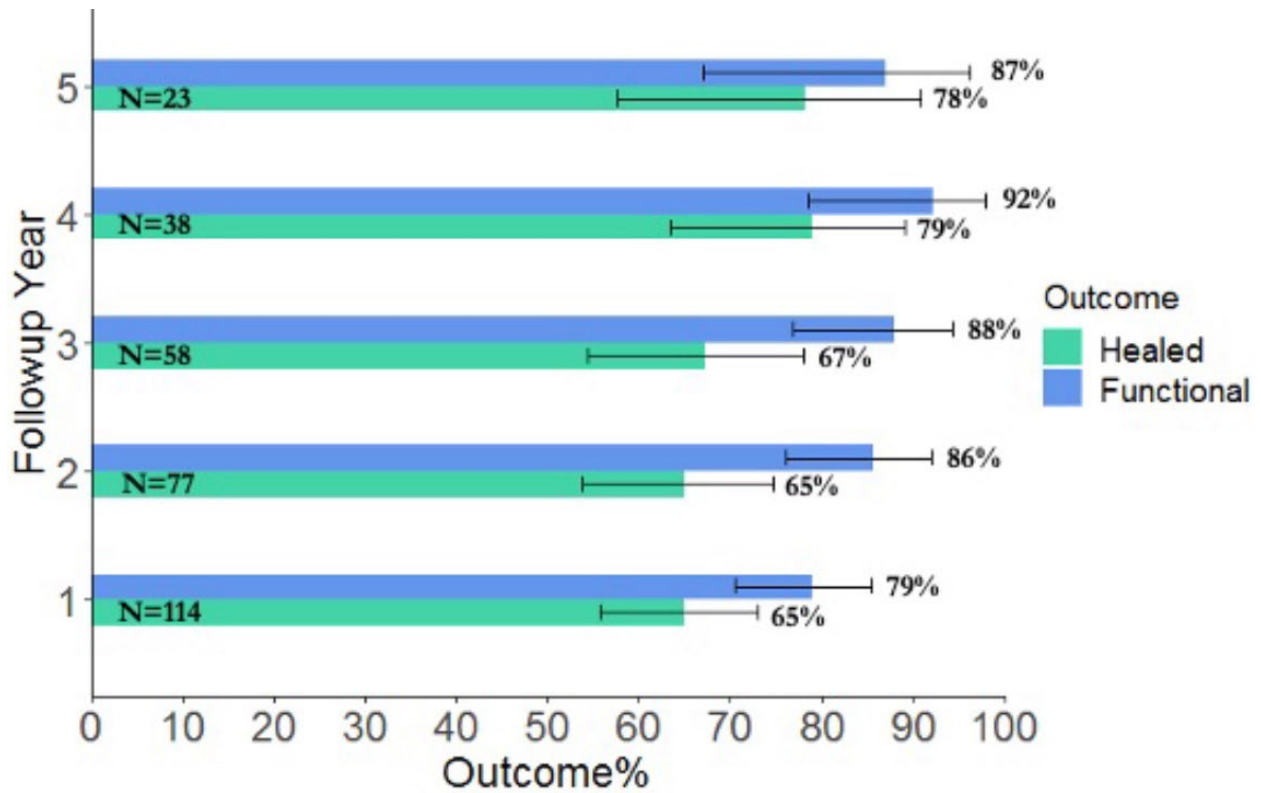
Thirty-two variables were collected for all subjects. However, only 12 described in literature as most likely to affect both the primary study aim and functionality were analyzed^{19,22}. In this interim analysis, the only variable significantly associated with healed outcomes was the presence of a post (p=0.019). Similarly, teeth diagnosed as ‘cracked’ requiring NSRCT were more likely to not be considered functional if missing a permanent crown (p=0.02).

- **Table 1.** The incidence of a crack for a particular tooth type expressed as a percentage, and the number of subjects

Tooth Type	Incidence	Number of Subjects
Mandibular 2nd Molar	38.5%	62
Mandibular 1st Molar	26.7%	43
Maxillary 1st Molar	16.8%	27
Maxillary 2nd Molar	9.3%	15
Maxillary 2nd Premolar	4.3%	7
Mandibular 2nd Premolar	1.9%	3
Maxillary 1st Premolar	1.2%	2
Mandibular 3rd Molar	0.6%	1
Maxillary Canine	0.6%	1



- Figure 1. Survival Analysis:** The estimated proportion surviving (not extracted) on the y-axis by any given time (x-axis). The cumulative 5-year survival was 79% (95% CI 71%-89%).



- Figure 2. Healed and Functional Analysis:** A horizontal bar graph depicting the outcomes at years 1-5 as either healed (green), or functional (blue). Error bars represent 95% confidence intervals.

Table 3: Characteristics by functional status at follow-up year 1

	Not Functional N= 24	Functional N=90	P value
Age	52.8 (12.4)	50.0 (11.3)	0.314
Gender:			
Female	5 (17.9%)	23 (82.1%)	0.83
Male	19 (22.1%)	67 (77.9%)	
Enrollment type:			
Prospective	23 (22.1%)	81 (77.9%)	0.68
Retrospective	1 (10.0%)	9 (90.0%)	
PreOp cold sensitivity:			
NR	7 (13.2%)	46 (86.8%)	0.12
R/L	11 (25.6%)	32 (74.4%)	
R/NL	6 (33.3%)	12 (66.7%)	
PreOp radiolucency:			
No	11 (21.2%)	41 (78.8%)	0.85
Yes	10 (17.9%)	46 (82.1%)	
PreOp pain	4.00 (3.15)	3.51 (3.11)	0.50
Pulpal Status			
Vital	17 (25.8%)	49 (74.2%)	0.23
Necrotic	7 (14.6%)	41 (85.4%)	
Permanent restoration at Follow-Up:			
No	5 (55.6%)	4 (44.4%)	0.02
Yes	19 (18.4%)	84 (81.6%)	
Intracanal post present at F/U:			
No	20 (18.9%)	86 (81.1%)	0.10
Yes	3 (50.0%)	3 (50.0%)	
Mesial marginal ridge crack:			
No	15 (20.0%)	60 (80.0%)	1.0
Yes	6 (21.4%)	22 (78.6%)	
Maximum Crack Distance	3.17 (0.75)	3.59 (2.65)	0.515
Distal marginal ridge crack:			
No	14 (21.5%)	51 (78.5%)	0.90
Yes	7 (18.4%)	31 (81.6%)	
Maximum Crack Distance	4.29 (2.29)	3.58 (1.39)	0.459
p values are from t-tests for continuous variable and Chi-square or Fisher's exact tests for categorical variables			

• **Table 3:** Characteristics by healed status at follow-up year 1

	Healed N= 74	Unhealed N=40	P value
Age	51.0 (10.9)	49.8(12.7)	0.61
Gender:			
Female	19 (67.9%)	9 (32.1%)	0.882
Male	55 (64.0%)	31 (36.0%)	
Enrollment type:			
Prospective	68 (65.4%)	36 (34.6%)	0.739
Retrospective	6 (60.0%)	4 (40.0%)	
PreOp cold sensitivity:			
NR	36 (67.9%)	17 (32.1%)	0.815
R/L	27 (62.8%)	16 (37.2%)	
R/NL	11 (61.1%)	7 (38.9%)	
PreOp radiolucency:			
No	37 (71.2%)	15 (28.8%)	0.348
Yes	34 (60.7%)	22 (39.3%)	
PreOp pain	3.78 (3.15)	3.30 (3.06)	0.431
Pulpal Status			
Vital	43 (65.2%)	23 (34.8%)	1.000
Necrotic	31 (64.6%)	17 (35.4%)	
Permanent restoration at Follow-Up:			
No	4 (44.4%)	5 (55.6%)	0.277
Yes	68 (66.0%)	35 (34.0%)	
Intracanal post present at F/U:			
No	72 (67.9%)	34 (32.1%)	0.019
Yes	1 (16.7%)	5 (83.3%)	
Mesial marginal ridge crack:			
No	52 (69.3%)	23 (30.7%)	0.802
Yes	18 (64.3%)	10 (35.7%)	
Maximum Crack Distance	3.67 (2.93)	3.20 (0.63)	0.524
Distal marginal ridge crack:			
No	41 (63.1%)	24 (36.9%)	0.242
Yes	29 (76.3%)	9 (23.7%)	
Maximum Crack Distance	3.62 (1.42)	4.00 (2.06)	0.617
p values are from t-tests for continuous variable and Chi-square or Fisher's exact tests for categorical variables			

CHAPTER 4: Discussion

This study defined healed endodontically treated cracked teeth as those without clinical signs and symptoms, a PAI score of 1 or 2 and no periodontal probing depth changes greater than 1.0 mm. This interim analysis found that the overall healing rate after one and two years was 65%, which was considerably lower than the reported one-year success rate of 82% in a similar study published by Krell¹⁹. However, it is worth noting that Krell's study did not define specific criteria for signs or symptoms that distinguished whether treatment was considered a success or failure, nor did it report any changes in probing depth, radiographic interpretation or any calibration methods and procedures¹⁹. Likewise, in a systematic review and meta-analysis, a success rate of 82% was reported after one year²². Meanwhile, Chen and Hsu's study reported a healing rate of 75.8%¹⁷, which is similar to this study's two-year healing rate of 65%. Several factors could be attributed to the lower overall healed rate in the current study, including the stringent radiographic and clinical criteria utilized to define healing, as well as limitations imposed by the study's conduction within a military endodontic residency program.

Despite lower healing rates than other comparable studies, our research demonstrated a two-year survival rate comparable to similar studies. Our survival findings indicate an 89% two-year survival rate for 88 teeth, which is consistent with the Kang et al. study reporting a 90% two-year survival rate for 88 cracked teeth that underwent NSRCT²³. Additionally, studies by Tan et al. and Chen et al. reported comparable two-year survival rates of 86% and 76% respectively^{17,24}.

Although our study had a smaller sample size for 4- and 5-year data compared to other similar studies, the Kaplan-Meier method was utilized to estimate survival probabilities based on data from 161 subjects. Our estimated 4-year survival probability of 82% is notably lower than

the 96% reported by Davis and Sharriff²⁰, who placed a resin modified glass ionomer to the extent of the radicular crack, a treatment not utilized within the current study's protocol.

Additionally, our estimated a 5-year survival probability of 79% (95% CI 71.2% - 87.8%) was comparatively lower than a previous retrospective study that evaluated 84 patients and found a 5-year survival rate of 92%²¹.

Based on the limited endodontically treated cracked tooth outcome literature available, it is expected that several variables could have an impact on the outcome. These variables include the crack's location, its extension onto the pulpal floor and root, periodontal probing depths greater than 5mm, and the preoperative periapical diagnosis. Regarding prevalence, many of the studies examined age, sex, tooth number, existing restorations and the terminal position within the dental arch^{19,20,21,22}. Past outcome studies have considered various factors that may impact the overall success of endodontically treated cracked teeth. Previous research has identified pocket depths greater than 5mm as the most significant factor related to failure, in which 41% resulted in a success. Additionally, the presence of a distal marginal ridge crack, as well as a periapical diagnosis of acute or chronic apical abscess, symptomatic apical periodontitis, and the presence of a post were also found to decrease the success rate¹⁹. It was also found that cracked teeth that underwent NSRCT and full-coverage restorations had a success rate of 93.6% after two years, compared to the success rate of 20% for teeth without such restorations¹⁹.

This interim analysis of variables related to endodontically treated cracked teeth revealed that the presence of a post was the sole factor that exhibited a negative influence on healing while the presence of a permanent crown was the only variable that affected functionality. One possible explanation for this finding is that the placement of posts is performed by restorative dentists not associated with the protocol of the study and who may not consistently use rubber

dam isolation during the post placement. The use of a rubber dam isolation during post placement can have a significant positive impact on the success rate²⁵. The presence of a distal marginal ridge crack, a probing depth greater than 5mm, and periapical status did not exhibit any statistically significant differences at the present time in this study. As the sample size reaches the targeted number of 250 and additional recall appointments are conducted, there should be sufficient data available for more comprehensive variable analysis.

Lack of a permanent crown was a contributing factor in the determination of whether a tooth was considered functional (lack clinical symptoms regardless of radiographic assessment). Full coverage restorations are the recommended treatment plan, as the cracked is splinted upon cementation of the crown, thus preventing the crack from propagating further apically causing additional periodontal destruction or pain²⁶. Although not specifically examined in this interim analysis, a potential area for future research involves investigating potential correlations between the placement of a permanent crown, clinical symptoms, crack propagation, and the development or resolution of periapical pathosis.

Among the cracked teeth observed in the current study, the mandibular 2nd molar (38.5%) was found to be the most common, followed by the mandibular 1st molar (26.7%) (Table 1). These findings align with prior research^{4,18,23} and support the notion that terminal teeth may have a higher likelihood of cracks²². The increased incidence of cracks in terminal teeth can be attributed to the physics of the temporomandibular joint, where greater force is exerted closer to the point of joint articulation²⁶.

The limitations of this study include limited eligible patient population, strict criteria for outcome and the personnel conducting the research. The participants were primarily active-duty service members, retirees, and their family members, who tend to relocate frequently every 2-3

years, resulting in declining recall rates over time. This study has spanned eight years to date, beginning in 2015, and has involved a rotation of calibrated board-certified endodontists who completed the PAI scoring, which could introduce inter-examiner variability. In previous research, radiographic interpretation agreement between examiners has been found to be 47%²⁷. Finally, the study relied on endodontic residents to obtain enrollments and follow-up data, and these residents varied year by year, introducing the possibility of inconsistency in the methods used to measure percussion, palpation, and probing depths, which could potentially affect the rates of healed and functional teeth.

CHAPTER 5: Conclusions

In this combined prospective and retrospective interim analysis, 161 endodontically treated cracked teeth were evaluated and demonstrated a one-year healed rate of 65% and a functional rate of 79%, with the presence of a post and unrestored crowns being the main contributors affecting healing rate and functionality. Although the 2-5 year data is not yet as extensive, it suggests a trend towards increased healing over time, which is consistent with previously published research indicating that radiographic healing can occur over an extended period^{28,29}. Many practitioners continue to deem teeth with cracks as non-restorable. This practice is purely anecdotal and not evidence based. Our data indicate that cracked teeth can be successfully retained as the estimated four and five-year survivability probability is 82% and 79% respectively. This study will continue to collect data for further analysis to provide greater insight into the outcome of cracked teeth after non-surgical root canal treatment.

APPENDIX A – Cracked Tooth Data Form

Subject# _____

PROTOCOL #410603-REGISTRY/CRACKED TOOTH DATA COLLECTION FORM

<p>1a. Tooth # _____</p> <p>1b. Position of tooth in arch: __ Terminal __ Non-terminal</p> <p>1c. Existing Restoration? Y/N (Material and surfaces): _____</p> <p>1d. Can Crack be visualized? Y/N (cont'd pg 2)</p> <p>1e. Method of crack diagnosis: __ Tooth Slooth __ Transilluminator __ Dye/Stain _____ Other: (List)</p>	<p>2a. Was treatment performed on day of diagnosis? Y/N</p> <p>2b. Treatment performed: __ Band placed __ Occlusal adjustment __ Provisional Crown __ NSRCT __ Permanent full coverage restoration _____ Other: (List)</p>
---	--

<p>3a. Does the patient have a history of Cracked Tooth on another tooth? Y/N</p> <p>3b. What was the treatment provided?</p> <p>3c. What was the outcome of cracked tooth listed in 3a?</p>
--

Date	Is tooth present?	Symptomatic Y/N	What tx has been performed since last visit?	RCT completed? (If yes, date)	Recall Method (phone, dental visit, or other)

APPENDIX B- Cracked Tooth Pre-Operative Data Form

Subject# _____

Visualization of Cracks in Tooth Pre-Treatment (at Evaluation)

Tooth number _____

Check the appropriate boxes/fill in blanks

Please fill in probing depths (mm)

	M	Mid	D
B			
L			

Date: _____

Did you visualize a crack at examination (Circle one)?

NO

YES



Location of Fracture
(check all that apply)

- Mesial Marginal ridge
- Distal Marginal ridge
- Occlusal Surface
- Buccal Groove
- Lingual Groove
- Other _____

Appendix C- Cracked Tooth Access Data Form

Subject# _____

Visualization upon endodontic ACCESS

Tooth number _____

Check the Appropriate boxes/Fill in blanks

Please fill in probing depths (mm)

	M	Mid	D
B			
L			

Date: _____

Did you visualize a crack upon access (circle one)?

NO YES



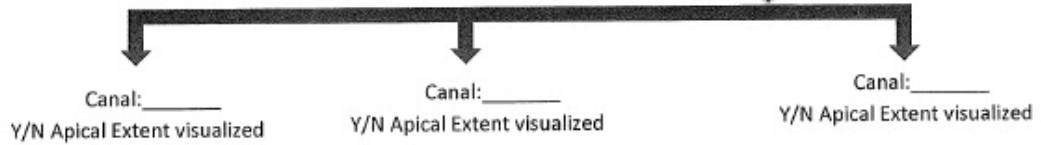
Location of Fracture (check all that apply)

- Mesial Marginal ridge
- Distal Marginal ridge
- Axial Wall _____
- Floor of chamber
- Other _____



Did the crack enter a canal?

NO YES



Appendix D- Registry/Cracked Tooth Pre-Operative Data Form

Subject #: _____

PROTOCOL #410603-REGISTRY/CRACKED TOOTH PREOPERATIVE DATA COLLECTION FORM

Tooth type: single root multiple root

Subject meets eligibility criteria (Y/N)

Does patient have any of the following conditions (circle):

Hypertension: B/P _____ Smoker Coronary Heart Disease Diabetes Type: _____

Symptoms: Y/N

- | | |
|---|---|
| <p>_____ Pain (0-10) (Y/N)</p> <p>_____ Can locate pain by quadrant (Y/N)</p> <p>_____ Can locate pain by tooth (Y/N)</p> <p>_____ Tooth #</p> <p>_____ /B0 Electric pulp tester</p> <p>_____ Palpation sensitivity</p> <p>_____ Sinus tract (Y/N)</p> <p>_____ Swelling (Y/N)</p> <p>_____ History of Ortho tx (Y/N)</p> <p>_____ History of external resorption (Y/N)</p> <p>_____ Post (Y/N)</p> <p>_____ Caries</p> | <p>_____ Cold sensitivity (R/NL; R/L; NR)</p> <p>_____ Percussion sensitivity (S/NS)</p> <p>_____ Mobility (Miller's Class)</p> <p>_____ Bleeding on probing</p> <p>_____ History of bleaching (Y/N)</p> <p>_____ History of internal resorption (Y/N)</p> <p>_____ Retreatment (Y/N)</p> <p>_____ Surgical/nonsurgical treatment</p> <p>_____ Open margin (Y/N)</p> <p>_____ Resorption present (Y/N)</p> <p>_____ Duration of symptoms (mos.)</p> <p>_____ Fracture (Y/N): Type _____</p> |
|---|---|

PPD (mm)	Buccal	Lingual
Mesial		
Direct		
Distal		

Preoperative Radiographic findings:

Intact lamina dura (Y/N) Radiolucency (Y/N) Size x mm

Preoperative Diagnosis:

- | | |
|--|--|
| <p style="text-align: center;">Pulpal:</p> <p>_____ Normal pulp</p> <p>_____ Reversible pulpitis</p> <p>_____ Symptomatic irreversible pulpitis</p> <p>_____ Asymptomatic irreversible pulpitis</p> <p>_____ Pulp necrosis</p> <p>_____ Previously treated</p> <p>_____ Previously initiated therapy</p> | <p style="text-align: center;">Apical:</p> <p>_____ Normal apical tissues</p> <p>_____ Symptomatic apical periodontitis</p> <p>_____ Asymptomatic apical periodontitis</p> <p>_____ Acute apical abscess</p> <p>_____ Chronic apical abscess</p> <p>_____ Condensing osteitis</p> <p>_____ Lesion of non endodontic origin</p> |
|--|--|

History of Trauma to tooth _____

Was CBCT Taken? _____

Appendix E- Registry/Cracked Tooth Intra-Operative Data Form

Subject #: _____

PROTOCOL #410603 REGISTRY/CRACKED TOOTH INTRAOPERATIVE DATA COLLECTION FORM

Working length established using electronic apex locator: Y/N

Patency Achieved: _____ Canal Y/N _____ Canal Y/N _____ Canal Y/N _____ Canal Y/N _____ Canal Y/N _____ Canal Y/N Was patency maintained throughout the procedure? _____ How often? _____	Anesthetic used (Carpules): 2% Lidocaine w/1:100,000 epi _____ 0.5% Marcaine w/1:200,000 epi _____ 4% Articaine w/1:100,000 epi _____ 3% Mepivivaine _____
--	---

Procedure Irrigant used, quantity (ml): _____ Method of Irrigation: _____ Side-vented tip _____ Passive ultrasonic _____ Neg. Pressure Ca(OH) ₂ used as interappointment medicament: Y/N Procedural complications: Y/N Type: _____ Intraorifice barrier placed: Y/N Type: _____ Number of treatment sessions: single multiple	Obturation: _____ Flush (≤2 mm from apex) _____ Overextension (beyond apex) _____ Underextension (>2 mm short of apex) Type of obturation material _____
Retreatments Type of obturation material removed: _____ Method of removal: _____	

Post treatment Diagnosis

Pupal

- _____ Normal pulp
- _____ Reversible pulpitis
- _____ Asymptomatic irreversible pulpitis
- _____ Symptomatic irreversible pulpitis
- _____ Pulp necrosis
- _____ Previously treated
- _____ Previously initiated therapy

Apical

- _____ Normal apical tissues
- _____ Symptomatic apical periodontitis
- _____ Asymptomatic apical periodontitis
- _____ Acute apical abscess
- _____ Chronic apical abscess
- _____ Condensing osteitis
- _____ Lesion of non endodontic origin

Date of Treatment Completion: _____

EVALUATOR USE ONLY Final treatment radiographic Periapical Index (PAI) score: 1 2 3 4 5

Appendix F- Registry/Cracked Tooth Follow-Up Data Form

Subject #: _____

PROTOCOL #410603-REGISTRY/CRACKED TOOTH FOLLOW-UP DATA COLLECTION FORM

Date of follow-up evaluation: _____

Does patient have any of the following conditions (circle):

Hypertension: B/P _____ Smoker _____ Coronary Heart Disease _____ Diabetes Type: _____

Symptoms: Y/N

- | | |
|--|---|
| <input type="checkbox"/> Pain (0-10)
<input type="checkbox"/> EPT/80
<input type="checkbox"/> Palpation sensitivity (S/NS)
<input type="checkbox"/> Sinus tract (Y/N)
<input type="checkbox"/> Swelling (Y/N)
<input type="checkbox"/> Time Elapsed Between Initial Tx and Permanent Restoration
<input type="checkbox"/> Duration of symptoms | <input type="checkbox"/> Cold sensitivity (R/NL, R/L, NR)
<input type="checkbox"/> Percussion sensitivity (S/NS)
<input type="checkbox"/> Mobility (Miller's Classification)
<input type="checkbox"/> Periodontal Screening Record (PSR)
<input type="checkbox"/> Bleeding on probing |
|--|---|

PPD (mm)	Buccal	Lingual
Mesial		
Mid		
Distal		

Follow-up Radiographic findings:

Intact lamina dura Y/N _____ Radiolucency (Y/N) Size _____ x _____ mm

Follow-up diagnosis: (Apical)

- | | |
|---|---|
| <input type="checkbox"/> Normal apical tissues
<input type="checkbox"/> Symptomatic apical periodontitis
<input type="checkbox"/> Asymptomatic apical periodontitis
<input type="checkbox"/> Acute apical abscess
<input type="checkbox"/> Chronic apical abscess
<input type="checkbox"/> Condensing osteitis
<input type="checkbox"/> Lesion of non endodontic origin | <input type="checkbox"/> Caries present? Y/N _____
<input type="checkbox"/> Permanent coronal restoration present? Y/N _____
<input type="checkbox"/> Intracanal post present? Y/N _____
<input type="checkbox"/> Open Margin Y/N? _____
<input type="checkbox"/> Surgical or Nonsurgical Treatment _____ |
|---|---|

EVALUATOR USE ONLY

Final treatment radiographic Periapical Index (PAI) score: 1 2 3 4 5

REFERENCES

1. AAE. Glossary of Endodontic Terms. 2020; 10th Edition
2. Nosrat A, Yu P, Verma P, et al. Was the Coronavirus Disease 2019 Pandemic Associated with an Increased Rate of Cracked Teeth? *J Endod* 2022;48(10):1241-47.
3. Gibbs JW. Cuspal Fracture Odontalgia. *Dent Digest* 1954; 60:158-160
4. Cameron CE. Cracked-Tooth Syndrome. *J Am Dent Assoc* 1964;68:405-11.
5. Stanley HR. The cracked tooth syndrome. *J Am Acad Gold Foil Oper* 1968;11(2):36-47.
6. Brannstrom M. The hydrodynamic theory of dentinal pain: sensation in preparation, caries, and the dentinal crack syndrome. *J Endod* 1986; 12:453-7.
7. AAE Colleagues for Excellence. Cracked teeth and vertical root fractures: A new look at a growing problem. *American Association of Endodontist*, 2022: 1-7
8. Talwar S, Utneja S, Nawal RR, et al. Role of Cone-beam Computed Tomography in Diagnosis of Vertical Root Fractures: A Systematic Review and Meta-analysis. *J Endod* 2016;42(1):12-24.
9. Hasan S, Singh K, Salati N. Cracked tooth syndrome: Overview of literature. *Int J Appl Basic Med Res* 2015;5(3):164-8.
10. Alaugaily I, Azim AA. CBCT Patterns of Bone Loss and Clinical Predictors for the Diagnosis of Cracked Teeth and Teeth with Vertical Root Fracture. *J Endod* 2022;48(9):1100-06.
11. Brady E, Mannocci F, Brown J, Wilson R, Patel S. A comparison of cone beam computed tomography and periapical radiography for the detection of vertical root fractures in nonendodontically treated teeth. *Int Endod J* 2014;47(8):735-46.
12. Makins SR. Artifacts interfering with interpretation of cone beam computed tomography images. *Dent Clin North Am* 2014;58(3):485-95.
13. AAE Colleagues for Excellence. Cracking the cracked tooth code: From unpredictability to predictability. *American Association of Endodontist*, 2008: 1-7.
14. Wu S, Lew HP, Chen NN. Incidence of Pulpal Complications after Diagnosis of Vital Cracked Teeth. *J Endod* 2019;45(5):521-25.
15. Berman LH, Kuttler S. Fracture necrosis: diagnosis, prognosis assessment, and treatment recommendations. *J Endod* 2010;36(3):442-6.
16. Ricucci D, Siqueira JF, Jr., Loghin S, Berman LH. The cracked tooth: histopathologic and histobacteriologic aspects. *J Endod* 2015;41(3):343-52.
17. Chen YT, Hsu TY, Liu H, Chogle S. Factors Related to the Outcomes of Cracked Teeth after Endodontic Treatment. *J Endod* 2021;47(2):215-20.
18. Krell KV, Rivera EM. A six year evaluation of cracked teeth diagnosed with reversible pulpitis: treatment and prognosis. *J Endod* 2007;33(12):1405-7.
19. Krell KV, Caplan DJ. 12-month Success of Cracked Teeth Treated with Orthograde Root Canal Treatment. *J Endod* 2018;44(4):543-48.
20. Davis MC, Shariff SS. Success and Survival of Endodontically Treated Cracked Teeth with Radicular Extensions: A 2- to 4-year Prospective Cohort. *J Endod* 2019;45(7):848-55.
21. Sim IG, Lim TS, Krishnaswamy G, Chen NN. Decision Making for Retention of Endodontically Treated Posterior Cracked Teeth: A 5-year Follow-up Study. *J Endod* 2016;42(2):225-9.

22. Olivieri JG, Elmsmari F, Miro Q, et al. Outcome and Survival of Endodontically Treated Cracked Posterior Permanent Teeth: A Systematic Review and Meta-analysis. *J Endod* 2020;46(4):455-63.
23. Kang SH, Kim BS, Kim Y. Cracked Teeth: Distribution, Characteristics, and Survival after Root Canal Treatment. *J Endod* 2016;42(4):557-62.
24. Tan L, Chen NN, Poon CY, Wong HB. Survival of root filled cracked teeth in a tertiary institution. *Int Endod J* 2006;39(11):886-9.
25. Goldfein J, Speirs C, Finkelman M, Amato R. Rubber dam use during post placement influences the success of root canal-treated teeth. *J Endod* 2013;39(12):1481-4.
26. Guthrie RC, DiFiore PM. Treating the cracked tooth with a full crown. *J Am Dent Assoc*. 1991; 122:71-3
27. Goldman M, Pearson AH. Endodontic success--who's reading the radiograph? *Oral Surg Oral Med Oral Pathol* 1972; 33(3):432-437.
28. Orstavik D. Time-course and risk analyses of the development and healing of chronic apical periodontitis in man. *Int Endod J* 1996; 29:150-5.
29. Ng YL, Mann V, Rahbaran S, Lewsey J, Gulabivala K. 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(12):921-39.