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OUTCOME OF ENDODONTICALLY TREATED CRACKED TEETH

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A thesis submitted to the Faculty of the
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ABSTRACT

OUTCOME OF ENDODONTICALLY TREATED CRACKED TEETH

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D.M.D., ENDODONTICS, 2021

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Introduction: A cracked tooth has been defined by the American Association of Endodontists as "an incomplete fracture initiated from the crown and extending subgingivally, usually directed mesiodistally." Pain to biting with temperature sensitivity is the most commonly reported symptom of patients presenting with a cracked tooth. An extensive crack can compromise the pulp and result in pulpal and/or periapical pathosis requiring non-surgical root canal treatment (NSRCT). Although reports of cracked teeth have been published in the literature since the 1950's, there are currently no long-term outcome studies on teeth diagnosed with a crack that have subsequently received NSRCT. **Objectives**: This prospective study will evaluate the outcome and identify co-variant factors affecting the outcome of endodontically treated cracked teeth over the course of 5 years. **Methods**: A research study is presently being undertaken at the Naval Postgraduate Dental School Endodontics Department following the outcome of teeth diagnosed as "cracked tooth", and subsequently receiving NSRCT. Six standardized forms are used to collect data with recall appointments performed annually for up to 5 years. A power analysis determined that 250 teeth will be needed to determine healed, non-healed, survival, and functional outcomes based on clinical and/or radiographic assessment. **Results**: One hundred forty-one teeth have been analyzed for this interim analysis. This cohort consists of 18 retrospective and 123 prospective subjects. Seventeen teeth were extracted and therefore not included in the data analysis. The median age of

subjects was 47 years old. The 1-year healed rate was 64% and the 1-year functional rate was 87%. One -year survivability was calculated to be 92%. At this time, a co-variant analysis could not be performed due to insufficient data. **Conclusion:** To date, of those cases presenting for recall examinations, the data indicated that endodontically treated cracked teeth have the opportunity to heal and remain functional, and therefore should not be immediately diagnosed as non-restorable.

TABLE OF CONTENTS

LIST OF TABLES vi

LIST OF FIGURES vii

LIST OF ABBREVIATIONS viii

CHAPTER 1: Introduction 1

CHAPTER 2: Review of the literature 3
- Literature search 3
- Etiology 3
- Prevalence 5
- Diagnosis 5
- Histopathology 6
- Treatment 7
- Prognosis 8

CHAPTER 3: Objective 10
CHAPTER 4: Materials and methods 11
CHAPTER 5: Results 14
CHAPTER 6: Discussion 18
CHAPTER 7: Conclusions 20

APPENDIX A Cracked tooth data form 21
APPENDIX B Cracked tooth pre-operative data form 22
APPENDIX C Cracked tooth access data form 23
APPENDIX D Registry pre-operative data form 24
APPENDIX E Registry intra-operative data form 25
APPENDIX F Registry follow-up data form 26

REFERENCES 27

LIST OF TABLES

Table 1. Healing and functional rates 14

Table 2. Incidence of tooth type 17

LIST OF FIGURES

Figure 1. 3-year healed/functional trend 15

Figure 2. Survivability analysis 16

LIST OF ABBREVIATIONS

AAE	American Association of Endodontists
IRB	Institutional Review Board
mm	millimeters
NPDS	Naval Postgraduate Dental School
NSRCT	non-surgical root canal treatment
PAI	periapical index
PARL	periapical radiolucency
>	greater than
<	less than

CHAPTER 1: Introduction

Cracks and fractures are phenomena in which there is a partial or complete separation of tooth structure. There are three categories of cracks and fractures: cracked and fractured cusps, vertical root fractures, cracked teeth and split teeth.[1] The first publication describing cracked teeth was written by Gibbs in 1954.[2] He outlined symptoms a patient would experience when a fracture occurred. Additionally, he is credited for using the term "cuspal fracture odontalgia."[2] Shortly thereafter, Ritchey reported 22 cases of tooth fracture that lead to inflammation of the pulp.[3] Several treatment modalities were described, some of which required root canal treatment and others needing only cuspal coverage crowns.[3] In 1964, Cameron reported on 50 cracked teeth and coined the term "Cracked Tooth Syndrome."[4] Some trends he noted were the mandibular second molar was most likely to be involved, the fracture had a tendency to involve distal marginal ridges and sometimes mesial marginal ridges.[4] Further defining the condition were Maxwell and Braly who pointed out that incomplete tooth fractures had been previously described by other authors.[5] They went on to describe two categories, fractures not involving the pulp and those in which irreversible damage has already been done to the pulp.[5]

As one might surmise, a plethora of classification systems have been proposed and used throughout the years. The "Cracked Tooth Syndrome" terminology proposed by Cameron has not been adopted in modern diagnostic classification systems. However it still lingers as a term used even though it is out-of-date.[4] Currently, the American Association of Endodontists (AAE), has defined the current classification used for cracked teeth.[6] The five types are: craze lines, fractured cusp, cracked tooth, split tooth and, vertical root fracture.[6] A craze line is the most superficial category, with the extent isolated to the enamel.[6] A fractured cusp is just that, a fracture that involves complete or incomplete fracture of a tooth cusp.[6] This will typically have

both a mesial or distal orientation as well as a buccal or lingual orientation, which by definition, will isolate a particular cusp.[6] A cracked tooth occurs when the fracture involves one or both of the marginal ridges and extends down the proximal surface.[6] A split tooth is a separation of the tooth structure from a fracture that typically extends though both marginal ridges and proximal surfaces.[6] The fracture separates the tooth into two separate pieces over a long period of time or may occur instantaneously.[6] A vertical root fracture starts at the root surface and extends coronally, it may be a complete separation or an incomplete separation of tooth structure.[6] It is possible for a vertical root fracture to be isolated to the root alone, or contrarily it can involve the anatomic crown. The vertical root fracture has a predilection to be oriented in the buccal-lingual orientation.[6] It is essential to know the classifications and how they differ. This will allow a practitioner to make the appropriated diagnosis, thus facilitating the treatment rendered.

CHAPTER 2: Review of the Literature

LITERATURE SEARCH

A review of the literature was completed during the month of November 2019 in the following peer reviewed literature databases: MEDLINE using PubMed, Embase using Elsevier, and Dentistry and Oral Sciences Source using EBSCO. No date limitations were applied to the search criteria. Search criteria of headings and keywords was in relation to cracked teeth. A total of three hundred and thirteen studies were populated from the databases. A provisional review of the abstracts was completed and correlated to the previous articles that were analyzed in past literature reviews. Two articles were identified to meet the criteria of relating to the research project, full length, and peer reviewed. Both are included in this current assessment of the literature pertaining to the Cracked Tooth research project at Naval Post Graduate Dental School. A similar search using the above criteria was conducted in the month of April 2021 and two additional articles were included.

ETIOLOGY

There are many proposed causes of fractures and cracks, one consensus among the literature is they are caused by multiple factors co-existing together which leads to a fracture. There are four overarching categories for each of the factors contributing to a cracked tooth as defined by Lynch and McConnell, they are as follows: restorative procedures, occlusal factors, developmental factors, and miscellaneous factors.[7] The most common single causes of incomplete fracture are masticatory in nature or caused by trauma.[8]

There are many considerations that fall into the restorative procedures category which contribute to fracture development, for example a large cavity preparation, a failure in cavity design or large carious lesions.[8] Furthermore, the loss of tooth structure during access and instrumentation during root canal treatment has shown an increased risk for a cracked tooth.[9] Teeth with restorations have a 29 times greater chance of fracture development as determined by Ratcliff and Becker.[9]

Some considerations that align with the occlusal factors category are factors such as "masticatory accidents, tight cusp-fossa relationships, steep intercuspation, and bruxism."[10] Another consideration to occlusal factors would be occlusal load; teeth that are closer to the temporomandibular joint have a higher occlusal load due to the "lever effect" increasing the likelihood of a cracked tooth.[11]

Some developmental factors that contribute to fracture formation are "deep occlusal grooves, pronounced vertical radicular groves, or a bifurcation." [8] Developmental factors are a major consideration and contribute to the 60.4% of cracked teeth that had no restorations.[12]

The miscellaneous factors category includes aspects of thermal cycling, foreign body and dental instrumentation.[7] Thermocycling results in the development of cracks that progressively increase in size and originate at the dentinoemamel junction.[13] One could speculate that this is due to the coefficient of thermal expansion difference between enamel and dentin. Some other factors that may increase the risk of fracture is loss of tooth structure due to bulimia or anorexia nervosa.[8]

PREVALENCE

There are two major publications on the prevalence of cracked teeth when evaluation a large sample. The first one was published in 2007 by Krell and Rivera, which examined patients in a private practice setting over a 6 year period.[14] Of the 8,175 teeth that were assessed in the study, 9.7% were diagnosed as a cracked tooth.[14] Later in 2016, Kang and Kim examined patients in a hospital setting over a 5 year period.[15] Of the 1,977 teeth that were assessed in the study, 8.9% were diagnosed as a cracked tooth, which aligns with the findings of Krell and Rivera.[15] There is some variation among publications in regards to the effects of age, some have shown an increase in incidence of cracked teeth as age increases.[15, 16] Other authors determined that cracked teeth were most common in patients in their 40's.[17, 12] In respects to tooth type, there is some variation in the literature but there is substantial evidence indicating that the mandibular second molar is the most likely to develop a crack.[4, 14, 15, 18, 19] When considering the predilection of a cracked tooth and gender there is substantial variation in the literature. Cameron in his 1976 publication stated that females were more than two times more likely to develop a fracture.[16] In contrast, others have found a predilection favoring males in regards to developing a fracture by approximate 4% according to Roh et al and 10% according to Kang et al.[12, 15]

DIAGNOSIS

The diagnosis is the justification for the treatment rendered, and thus accuracy is crucial. First and foremost a thorough medical and dental history should be obtained. The past treatment rendered, if there has been subsequent visits in the past for the same tooth. The presence of parafunctional habits should be determined. The history of symptoms and if there has been any changes to the symptoms. Clinically, the symptoms vary widely, with the possibility of

sensitivity to hot or cold, discomfort when chewing, but the most common symptom being pain to pressure.[4] Cameron discussed the use of percussion tests, taping on teeth or cusps in all directions to locate the offending tooth. Cameron advocated, for having the patient bite a wooden toothpick which could also isolate the tooth, this is commonly known as a bite test.[4] Many items have been used for the bite test, from saliva ejectors to cotton rolls, to the commercially available Tooth Slooth. Furthermore, Cameron discussed transillumination, as well as staining with iodine or mercurochrome, today methylene blue is commonly used.[4] The dye will soak into the crack and after clearing away the excess, will highlight the fracture line, giving a visual cue of where the fracture is located. Transillumination is where a light source is used directly on the tooth. A fracture line will not allow the transmission of light throughout the tooth, and will act as an abrupt line where the light has been stopped. Abou-Rass in 1983 described other methods for determining the presence of a fracture to include removing existing restorations to directly visualize the fractures, radiographic visualization, clinical fragment separation, and surgical exploration to aid in direct visualization.[20] Additionally, the use of microscopic evaluation with at least 14x magnification is optimal for locating and evaluating cracks.[21] Finally, periodontal data collection and vitality testing on the teeth of interest will aid in diagnosis of a cracked tooth.[6] The proper diagnosis is essential because it will ensure that the correct treatment is rendered.

HISTOPATHOLOGY

It has been clearly shown that there is bacterial contamination of cracks in teeth. Kahler and colleagues in 2000 examined 20 teeth with fractured cusps and determined that there was indeed bacterial colonization of the dentinal surfaces of the fractured areas.[22] The histopathology

of cracked teeth was discussed by Ricucci and colleagues and published in 2015.[23] They studied 12 posterior cracked teeth with various depths of cracks. All of the cracks were colonized with bacterial biofilms. If the crack extended into the dentin, then the dentinal tubules were colonized with bacteria. They noted inflammatory cells in the pulp next to the infected dentinal tubules. There were variations on the effect to the pulp depending on the depth of the crack, from pulpal inflammation to pulpal necrosis. The pulpal response varied based on the "location, direction and extent of the crack but overall all cracks always colonized by bacterial biofilms."[23]

TREATMENT

The treatment of a cracked teeth is determined by the location and extent of the fracture and just as importantly the pulpal and periapical diagnosis.[6] If a pulpal or periapical diagnosis warrants root canal treatment then this must be completed before cuspal coverage. The purpose of treating a cracked tooth is to prevent the movement and further propagation of the fracture.[24] There are several immediate treatment options for a cracked tooth which are as follows: occlusal adjustment, removal of the involved segment, immobilize involved segment, copper ring placement, orthodontic band placement, temporary crown placement, or a direct composite splint.[24] In 2007, Signore et al reported on the use of bonded indirect composite onlays for the treatment of cracked teeth over a minimum of a 4 year period. It was determined that the 6-year survival was 93%, and the 7% that failed, required root canal treatment.[26] The next year, in 2008, Opdam and Roeters restored cracked teeth with direct composite restorations with no failures at a 7-year follow-up.[26] However, if there was no cuspal coverage restoration placed there was an annual failure rate of 6%.[26] In 2009, Abbott and Leow treated 100 cracked teeth with conservative treatment, which for a majority of teeth was the placement of a Glass Ionomer

restoration and stainless steel band.[27] They determined that root canal treatment was needed in 20% of cases that were diagnosed with reversible pulpitis and treated conservatively.[27]

Currently, the recommended treatment for cracked teeth without periapical or pulpal pathology is full cuspal coverage.[11, 28] In 1991, Guthrie and Difiore treated 28 cracked teeth with full coverage acrylic resin crowns, of which 25 remained symptom free one year after being restored; the remaining three required root canal treatment.[28] When a cracked tooth has been diagnosed with reversible pulpitis and a full cuspal coverage crown is placed, 21% required root canal treatment within a year.[14] If symptoms persist after root canal treatment, or if the crack involves the pulpal floor, or extends below the level of the bone the only feasible option is extraction.[15]

PROGNOSIS

In 2006, Tan et al assessed 50 cracked teeth that underwent root canal treatment at 2 years to determine the survival rate. They determined that the survival rate was approximately 86% with multiple cracks, terminal teeth in the arch, and pre-root filling periodontal pocketing greater than 3 mm being significant prognostic factors for survival.[29] In 2016, Sim et al published a 5-year retrospective study on the survival of 84 cracked teeth that had root canal treatment completed by endodontists.[18] They determined that the survival rate was 92% with cracks radicular cracks or cracks extending onto the pulpal floor being significant prognostic factors for survival.[18] In that same year, Kang and colleagues published a 2 year survival assessment of 88 cracked teeth that received root canal treatment by an endodontist.[15] They determined that the survival rate was 90% with periodontal pocketing greater than 6 mm being a significant prognostic factors for survival. In 2018, Krell and Caplan published a retrospective 1

year success rate of 363 cracked teeth that received root canal treatment in a private practice over a 25 year period.[19] They determined that the 1 year success rate was 82% with marginal ridge cracks, periodontal pocketing greater than 4 mm, diagnosis of chronic apical periodontitis, suppurative apical periodontitis or acute apical abscess being significant prognostic factors for survival.[19] In 2019, Davis and Shariff determined the success and survival of endodontically treated cracked teeth wherein the crack had a radicular extension.[30] Survival was determined as an asymptomatic, functional and present tooth and success was when no pathology, or symptoms are present and the tooth had been restored with a crown in occlusion. Overall, 59 teeth were evaluated with 100% survival rate at 2 years and approximately 97% at 4 years. Furthermore, there was approximately a 91% success rate at 2- to 4- year term.[30] The high success rate could be attributed to the placement of an intraorifice barrier "2-3 mm apical to the deepest extent of the radicular crack" using a bonded resin material.[30] It could be postulated that this sealed off the cracks from further bacterial ingress and possibly prevented further propagation of the cracks. Be that as it may, the major limitation of the study is the small sample size. Thus, there is still limited data on the long-term survival of endodontically treated teeth that have also been diagnosis with a crack, therefore more research is needed in this area.

CHAPTER 3: Objective*

**This study, WRNMMC IRB #410603, "Outcome of Endodontically Treated Cracked Teeth", is ongoing. The Objective section for this paper was taken from the approved protocol.*

The purpose was to determine the outcome of teeth diagnosed with cracked tooth requiring initial NSRCT at a minimum of 12 months after receiving treatment using clinical and radiographic data.

This study will assess the outcome of teeth diagnosed with cracked tooth that require initial NSRCT. Radiographic PAI scoring and the presence or absence of clinical symptoms will be collected at a minimum of 12 months following treatment to establish proportions of healed and not healed teeth. Healed teeth will have a PAI score of 1 or 2 AND are asymptomatic at recall. Teeth will be classified as not healed if they are symptomatic OR have a PAI score of 3, 4, or 5.

A secondary analysis using only the presence or absence of clinical symptoms will be used to establish the proportion of teeth that are functional.

CHAPTER 4: Materials and Methods*

**This study, WRNMMC IRB #410603, "Outcome of Endodontically Treated Cracked Teeth", is ongoing. The Objective section for this paper was modified from the approved protocol.*

This study retrospectively and prospectively collected data 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 a 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. For the retrospective portion, subjects were enrolled if cracked tooth details were noted retrospectively in the patient's record during a routine follow-up examination. An associate investigator obtained informed consent from the subject and all subjects were enrolled in the NPDS Endodontic Treatment Registry; WRNMMC #352271, a database of patients maintained in the NPDS Endodontic Department. The Endodontic Treatment Registry (WRNMMC #352271) was closed in Oct 2019 but subjects that were entered into WRNMMC IRB #410603, "Outcome of Endodontically Treated Cracked Teeth" prior to this closure have been retained.

Cracked tooth information was collected during the initial evaluation including tooth characteristics, diagnostic methods, fracture location as well as health history, history of present

condition and diagnostic test results (see APPENDIX A, B, D). Following the collection of pre-treatment data, non-surgical root canal therapy was provided. Subjects with previously initiated therapy from other clinics (i.e. pulpotomy or pulpectomy) were excluded from this study. Teeth were accessed using rubber dam isolation; information regarding crack location and extent was collected after access (see APPENDIX C). No specified instrumentation technique, irrigation technique, or obturation technique was required, and all were documented on standardized data forms (see APPENDIX E). 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 (see APPENDIX F). 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 using the Periapical Index (PAI) as defined by (Orstavik, et al. 1986). 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 had no signs or symptoms (mobility < class 2, probing depth < 5mm, and no swelling, sinus tract, percussion sensitivity, or palpation sensitivity) and 2) the PAI score was 1 or 2. A tooth was considered non-healed if: 1) the tooth presented with signs or symptoms or 2) the PAI score was 3, 4, or 5. In a separate analysis, all asymptomatic teeth (no percussion or palpation sensitivity), regardless of PAI score,

were considered functional (clinical success). All present (non-extracted) teeth regardless of symptoms were considered survived. The data were analyzed using R statistical software.

Based on previously published literature, a healed rate of 70% with a 95% confidence interval 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 207 subjects, with an allowance of up to 250 subjects if more were lost to recall than expected.

CHAPTER 5: Results

In this interim analysis, there are 18 retrospective subjects and 123 prospective subjects for a total of 141 subjects enrolled. There were 17 extracted teeth that were not included in the healed and functional analysis. There were 98 one-year recalls, 58 two-year recalls, 33 3-year recalls, 15 4-year recalls and 7 5-year recalls utilized for evaluation. The healing rate which is defined as the teeth being present, have no signs or symptoms and have a PAI score of 1 or 2. The functional rate is defined as the teeth are present and asymptomatic. The healing rates for years 1, 2 and 3 are 64%, 69% and 68% respectively (Table 1). The functional rates for years 1, 2 and 3 are 87%, 86% and 84% respectively (Table 1). The visual representation of this data is displayed in figure 1.

Table 1. The 3-year healing and functional trend results, expressed as a percentage.

Follow up Year	Healed	Functional
1	64%	87%
2	69%	86%
3	68%	84%

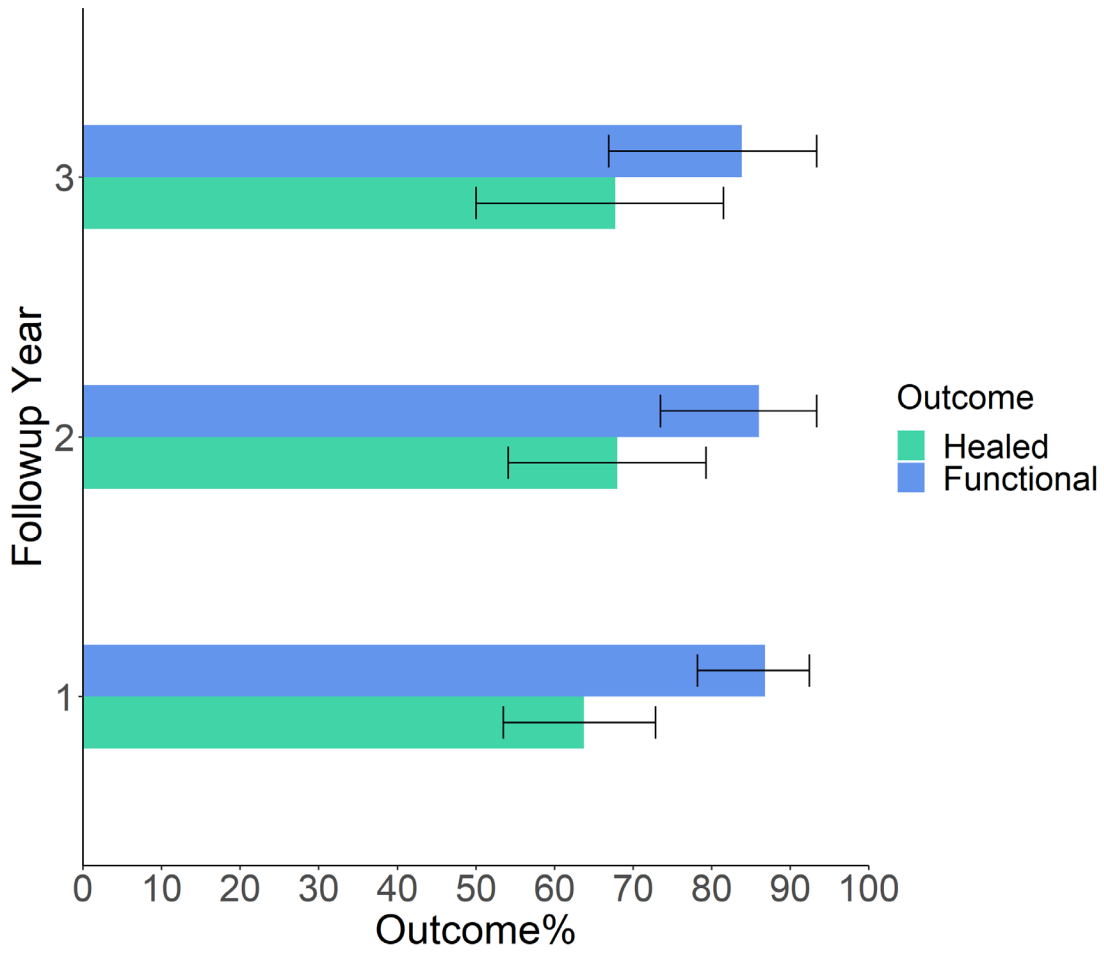

Figure 1. A horizontal bar graph depicting the outcome at years 1 though 3 as either healed, shown in green or functional, shown in blue. The standard deviation is depicted as a bracket.

The survivability analysis is shown in figure 2. This utilizes the information from the outcome percentages from figure 1, but also includes extracted teeth. A tooth was considered as survived if it was still present regardless of signs, symptoms and radiographic findings. As shown in figure 2, as time progresses in years the percent survivability decreases and the confidence interval increases. The 1-year survivability rate was 92 percent and the 2-year survivability rate was 89 percent.

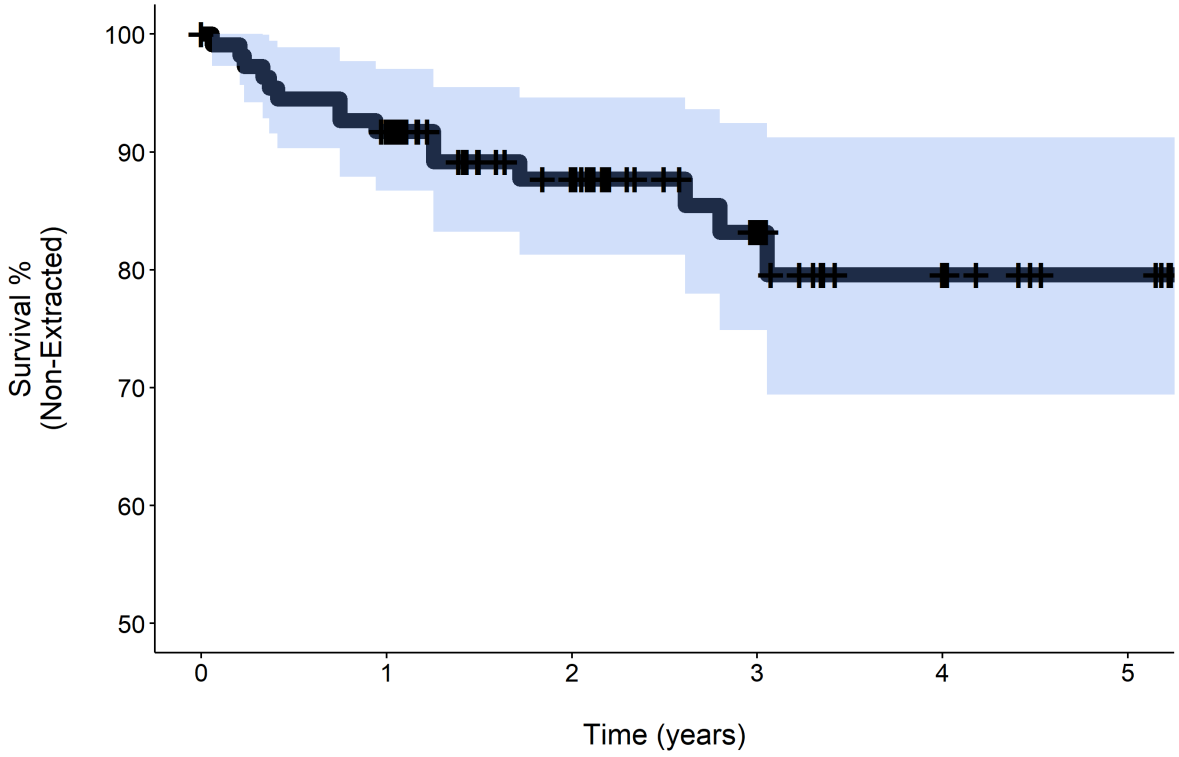

Figure 2. A line graph depicting the percent survivability over the course of 5 years. The blue shaded area is the confidence interval.

The Incidence of a crack in a particular tooth is shown in descending order of incidence in table 2. The highest incidence at 39.7 percent, was the mandibular 2nd molar. This was followed by the mandibular 1st molar and maxillary 1st molar at an incidence of 25.5 and 17.7 percent respectively. In regards to gender, 72.8 percent of subjects are male and 27.2 percent of subjects are female. The median age was 47 years old.

Table 2: The incidence of a crack for a particular tooth type expressed as a percentage, as well as the number of subjects.

Tooth Type	Incidence	Subjects
Mandibular 2nd molar	39.7%	56
Mandibular 1st molar	25.5%	36
Maxillary 1st molar	17.7%	25
Maxillary 2nd molar	8.5%	12
Maxillary 2nd premolar	4.3%	6
Mandibular 2nd premolar	2.1%	3
Maxillary 1st premolar	0.7%	1

CHAPTER 6: Discussion

There is defined and strict criteria for a tooth to be considered as healed in this study. This resulted in a 64 percent healing rate a one year, that is these are the teeth without any clinical signs or symptoms and have a PAI score of a 1 or 2. Studies that have higher healing rates, such as Krell & Caplan in 2018 and the meta-analysis in 2020 by Olivieri & Elmsmari, do not define the clinical signs and symptoms for a tooth to be categorized as healed.[19,31] In the Krell, 2018 and the Olivieri, 2020 the success rate at the one year mark was 82 percent. Not considering standard deviation, this is a healing rate that is 18 percent higher than the current study. Again, the differences in how a tooth is defined as healed is likely the reason for the discrepancy.

The incidence of a particular tooth type to become cracked was determined to be approximately 40 percent for mandibular 2nd molars followed by mandibular 1st molars at approximately 26 percent. This rate of occurrence aligns with many of the studies on cracked teeth. There is a tendency for the most posterior teeth to have a higher incidence of a crack. From a biomechanical prospective the jaw is a third-class lever system, and thus a higher amount of force can be applied at a point closer to the point of articulation. This would explain the preponderance of literature that shows molars having a higher incidence than premolars.[16, 19]

In a recent publication by Chen and colleagues in 2021, the healed rate was determined to be 75.8% at 23.3 months.[32] The two-year healed rate for this study is 69%. Furthermore, they determined that a preoperative periapical lesion, lack of a permanent restoration or a post was placed all significantly decreased the success rate.[32] There is currently not enough data for co-variate analysis of factors such as those presented by Chen and colleagues. As more recalls are

completed and more data gathered, there will be an increased likelihood that factors such as age, gender, probing depths, radiographic findings and clinical signs will affect the outcome.

A limitation of this study is the small sample size at this time. Overall, there is a sizable number of subjects enrolled; however, this does not directly correlate to recall data, which is what was used in the statistical analysis. This is a 5-year study and the number of recalls at the 3, 4, and 5 years are lower than ideal. Furthermore, the patient population is made up of primarily active duty military or recently retired personnel. This patient pool is highly migratory and change locations approximately every 2 to 3 years. This is objectively seen with the 1-year, 2-year and 3-year recall rates at 75 percent, 62 percent and 47 percent respectively. This study was started in 2015 and has been actively collecting data for over 6 years now. Due to the transient population, it is not unreasonable to estimate that this study will proceed for another 5 years for the target sample size to be met. Finally, it is still unclear at this time what effects that the novel severe acute respiratory syndrome coronavirus 2 had on the data. During the shutdown period, recalls were stopped for over 4 months. It will become clear as more data is collected if a statistically significant effect occurred, but a preliminary assessment is showing it had no effect.

CHAPTER 7: Conclusions

In conclusion, the outcome of endodontically treated teeth diagnosed with a crack at 1-year is 64 percent healed and 87 percent functional. The 1-year survivability rate is 92 percent. In regards to incidence, molars are more likely than premolars to have a crack. Cracked teeth have an opportunity to heal and to remain functional, and thus should not be deemed non-restorable. As this study gathers more data, many of the limitations will be overcome and the ability to do a co-variable analysis will become viable.

APPENDIX A

Subject#_____

PROTOCOL #410603-REGISTRY/CRACKED TOOTH DATA COLLECTION FORM

1a. Tooth #_____

1b. Position of tooth in arch: ___Terminal
___Non-terminal

1c. Existing Restoration? Y/N
(Material and surfaces):
_____

1d. Can Crack be visualized? Y/N (cont'd pg 2)

1e. Method of crack diagnosis: ___Tooth Slooth
___Transilluminator
___Dye/Stain
_____Other: (List)

2a. Was treatment performed on day of diagnosis? Y/N

2b. Treatment performed: __ Band placed
__Occlusal adjustment
__Provisional Crown
__NSRCT
__Permanent full coverage restoration
_____Other: (List)

3a. Does the patient have a history of Cracked Tooth on another tooth? Y/N

3b. What was the treatment provided?

3c. What was the outcome of cracked tooth listed in 3a?

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

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

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

Canal:_____
Y/N Apical Extent visualized

Canal:_____
Y/N Apical Extent visualized

Canal:_____
Y/N Apical Extent visualized

APPENDIX D

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

_____ Pain (0-10) (Y/N)
_____ Can locate pain by quadrant (Y/N)
_____ Can locate pain by tooth (Y/N)
_____ Tooth #
_____ /80 Electric pulp tester
_____ Palpation sensitivity
_____ Sinus tract (Y/N)
_____ Swelling (Y/N)
_____ History of Ortho tx (Y/N)
_____ History of external resorption (Y/N)
_____ Post (Y/N)
_____ Caries

_____ Cold sensitivity (R/NL; R/L; NR)
_____Percussion sensitivity (S/NS)
_____ Mobility (Miller's Class)
_____ Bleeding on probing
_____ History of bleaching (Y/N)
_____ History of internal resorption (Y/N)
_____ Retreatment (Y/N)
_____ Surgical/nonsurgical treatment
_____ Open margin (Y/N)
_____ Resorption present (Y/N)
_____ Duration of symptoms (mos.)
_____ Fracture (Y/N): Type_____

PPD (mm)	Buccal	Lingual
Mesial		
Direct		
Distal		

Preoperative Radiographic findings:

Intact lamina dura (Y/N) Radiolucency (Y/N) Size__x_____mm

Preoperative Diagnosis:

Pulpal:

_____ Normal pulp
_____ Reversible pulpitis
_____ Symptomatic irreversible pulpitis
_____ Asymptomatic 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

History of Trauma to tooth_____

Was CBCT Taken?_____

APPENDIX E

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

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 initated 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

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

_____Pain (0-10)
_____ EPT/80
_____Palpation sensitivity (S/NS)
_____Sinus tract (Y/N)
_____Swelling (Y/N)
_____ Cold sensitivity (R/NL, R/L, NR)
_____ Percussion sensitivity (S/NS)
_____ Mobility (Miller's Classification)
_____ Periodontal Screening Record (PSR)
_____ Bleeding on probing
_____ Time Elapsed Between Initial Tx and Permanent Restoration
_____Duration of symptoms

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)

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

Caries present? Y/N
Permanent coronal restoration present? Y/N
Intracanal post present? Y/N
Open Margin Y/N?
Surgical or Nonsurgical Treatment

EVALUATOR USE ONLY

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

REFERENCES

1. Hargreaves K, Berman L. Cohen's Pathways of the Pulp. St. Louis, Elsevier, 2016, pg 793.
2. Gibbs J. Cuspal fracture odontalgia. Dent Dig. 1954;60:158–60.
3. Ritchey B, Mendenhall R, Orban B. Pulpitis resulting from incomplete tooth fracture. Oral Surg Oral Med Oral Pathol. 1957;10:665–70.
4. Cameron C. Cracked-tooth syndrome. J Am Dent Assoc. 1964;68:405–11.
5. Maxwell H, Braly V. Incomplete tooth fracture. Prediction and prevention. CDA J. 1977;5:51–5.
6. American Association of Endodontists. Endodontics: Colleagues for Excellence – Cracking the Cracked tooth code. Summer 2008.
7. Lynch C, McConnell R. The cracked tooth syndrome. J Can Dent Assoc. 2002;68:470–5.
8. Geursten W, Schwarze T, Gunay H. Diagnosis, therapy, and prevention of the cracked tooth syndrome. Quintessence Int 2003;34:409-17.
9. Ratcliff S, Becker M, Quinn L. Type and incidence of cracks in posterior teeth. J Prosthet Dent. 2001;86:168–72.
10. Gutmann J, Rakusin H. Endodontic and restorative management of incompletely fractured molar teeth. Int Endod J. 1994;27:343–8.
11. Hiatt W. Incomplete crown-root fracture in pulpal-periodontal disease. J Periodontol. 1973; 44:369–79.
12. Roh B, Lee Y. Analysis of 154 cases of teeth with cracks. Dent Traumatol. 2006;22:118–23.
13. Brown W, Jacobs R, Thompson E. Thermal fatigue in teeth. J Dent Res. 1972;51:461.
14. Krell K, Rivera E. A six-year evaluation of cracked teeth diagnosed with reversible pulpitis: treatment and prognosis. J Endod. 2007; 33:1405–1427.
15. Kang SH, Kim BS, Kim Y. Cracked Teeth: Distribution, Characteristics, and Survival after Root Canal Treatment. J Endod. 2016;42:557–62.
16. Cameron C. The cracked tooth syndrome: additional findings. J Am Dent Assoc. 1976; 93:971– 85.
17. Seo D, Yi Y, Shin S, Park J. Analysis of factors associated with cracked teeth. J Endod 2012;38:288–92.
18. Sim I, Lim T, Krishnaswamy G, Chen N. Decision making for retention of endodontically treated posterior cracked teeth: A 5 year follow-up study. J Endod. 2016;42:225-9.
19. Krell K, Caplan D. 12-month success of cracked teeth treated with orthograde root canal treatment. J Endod. 2018;44:543–8.
20. Abou-Rass M. Crack lines: the precursors of tooth fractures—their diagnosis and treatment. Quintessence Int. 1983;14:437–47.
21. Clark D, Sheets C, Paquette J. Definitive diagnosis of early enamel and dentin cracks based on microscopic evaluation. J Esthet Restor Dent. 2003;15:391–401.
22. Kahler B, Moule A, Stenzel D. Bacterial Contamination of Cracks in Symptomatic Vital Teeth. J Endod. 2000;3:115–8.
23. Ricucci D, Siqueira J, Loghin S, Berman H. The cracked tooth: histopathologic and histobacteriologic aspects. J Endod. 2015; 41:343–52.

24. Banerji S, Mehta B, Millar BJ. Cracked tooth syndrome. Part 2: restorative options for the management of cracked tooth syndrome. British Dent J 2010;208:503-14.
25. Signore A, Benedicenti S, Covani U, Ravera G. A 4- to 6-year retrospective clinical study of cracked teeth restored with bonded indirect resin composite onlays. Int J Prosthodont. 2007;20:609–16.
26. Opdam N, Roeter J, Frencken J, Bronkhorst E, Truin G. Seven-year clinical evaluation of painful cracked teeth restored with a direct composite restoration. J Endod. 2008;34:808–11.
27. Abbott P, Leow N. Predictable management of cracked teeth with reversible pulpitis. Aust Dent J. 2009; 54:306-15.
28. Guthrie RC, DiFiore PM. Treating the cracked tooth with a full crown. J Am Dent Assoc. 1991;122:71–3.
29. 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.
30. Davis M, Shariff S. Success and Survival of Endodontically Treated Cracked Teeth with Radicular Extensions: A 2- to 4-year Prospective Cohort. J Endod. 2019;45:848–55.
31. Olivieri JG, Elmsmari F, Miro Q, Ruiz X, Krell KV, Garcia-Font M, Duran-Sindreu F. Outcome and survival of endodontically treated cracked posterior permanent teeth: a systematic review and meta-analysis. J Endod 2020; 46:455-63.
32. Chen YT, Hsu TY, Liu H, Chogle S. Factors Related to the Outcomes of Cracked Teeth after Endodontic Treatment. J Endod 2021;47:215-20.