Diagnosis of Cracked tooth and its Correlation of Root Canal Treatment using Quantitative Light-induced Fluorescence (QLF) Technology : a Retrospective study

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Diagnosis of Cracked tooth and its Correlation of Root Canal Treatment using Quantitative Light-induced Fluorescence (QLF) Technology : a Retrospective study

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Soyeon Yang

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This Certifies that the Master's Thesis
of Soyeon Yang is approved.

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감사의 글

석사논문을 마무리하면서, 많은 분들의 도움과 지지가 없었다면 해낼 수 없었을 많은 일들이 떠오릅니다. 석사과정과 본 학위논문을 준비하고 완성할 수 있도록 아낌없는 도움과 격려를 주신 분들께 감사의 인사를 전하고자 합니다.

먼저, 항상 부족했던 저를 열정과 조언으로 지도해 주셔서 본 학위논문을 완성할 수 있게 이끌어 주신 박정원 교수님께 깊은 존경과 감사를 전하고 싶습니다. 교수님의 세심한 지도와 따뜻한 격려 덕분에 논문을 무사히 마칠 수 있었습니다. 또한, 바쁘신 와중에도 논문 심사를 맡아 부족한 부분을 채워 주시고 꼼꼼히 검토해 주셨던 신수정 교수님과 전미정 교수님께도 감사드립니다. 교수님들 덕분에 논문이 한층 더 발전할 수 있었습니다.

늘 제자들의 수련 생활과 학문적 역량을 기르는데 헌신하시는 치과보존과 교수님들께도 감사의 말씀을 드립니다. 보존학을 공부하는 학생으로서 필수적인 소양들을 일깨워 주신 노병덕 교수님, 박성호 교수님, 김의성 교수님, 정일영 교수님, 신유석 교수님, 김선일 교수님, 김도현 교수님께도 깊이 감사드립니다. 앞으로도 이 고마움을 잊지 않고 더 나은 치과보존과 전문의가 되도록 노력하겠습니다.

또한, 학부 생활을 거쳐 대학원에 함께 진학하여 수련 받으며 큰 의지가 되어준 동기 오가영 선생에게 특별히 고맙고, 많은 지지와 격려를 보내준 의국 선후배님들께도 크나큰 감사의 말을 전합니다.

마지막으로, 끝없는 애정으로 항상 믿고 응원해주시는 부모님과 동생, 든든한 버팀목으로 언제나 제 편이 되어주는 사랑하는 남편과 우리의 새로운 가족 한방이에게도 사랑의 말을 전합니다.

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Cracked teeth present a diagnostic and treatment challenge due to their complicated etiology and often unstable prognosis. Quantitative light-induced fluorescence (QLF) technology detects red fluorescence caused by bacterial byproducts like porphyrins, showing potential for diagnosing and quantifying the extent of cracked teeth. This

retrospective study explores the potential of QLF technology for the diagnosis of cracked teeth and its utility in predicting their prognosis related to root canal treatment (RCT).

QLF compares the image captured in natural light with the fluorescence image taken at 405 nm wavelength, analyzes the mean values of fluorescence loss (ΔF) and red fluorescence (ΔR) between the images, and calculates ΔF, ΔFmax (the highest value of the fluorescence loss), ΔR, and ΔRmax (the highest value of red fluorescence).

Two hundred and seven cracked teeth from 149 patients diagnosed between April 2019 and April 2023 at Gangnam Severance Dental Hospital were included, examining their clinical characteristics including age, sex, percussion/sensibility/bite test, and crack direction. To statistically analyze the correlation between the collected data and clinical features, independent sample t-tests, analysis of variance, Pearson's correlation analysis, and post-hoc analyses were performed. Additionally, univariate regression analysis was conducted to compare which of the four QLF analysis values had the closest relationship with the RCT status that we aimed to investigate.

Of the 207 cracked teeth, 44 teeth (21.3%) underwent RCT and 4 out of 207 (1.9%) were extracted during follow-up (mean 19.1 months). QLF parameters differed significantly between teeth receiving restorative treatment versus RCT ($p < .0001$). Cracked teeth with $\Delta F < -10$, $\Delta Fmax < -30$, $\Delta R > 15$, or $\Delta Rmax > 30$ had around 60% probability of necessitating RCT ($p < .05$), exhibiting varying timelines for initiating RCT. Logistic regression confirmed all four QLF parameters correlated with RCT probability ($p < .0001$).

Cracked teeth with ΔR > 15 or ΔRmax > 30 tended to undergo RCT (61.1% and 60.0%, respectively) within 60 days after diagnosis.

The result of this study emphasizes the importance of sufficient monitoring before definitive restoration. The study underlines the QLF technology's utility for cracked teeth diagnosis and treatment decisions-making supported by evidence, despite certain limitations. Further prospective studies with standardized protocols are warranted to validate and refine the application of QLF in clinical settings and establish quantitative guidelines for cracked teeth diagnosis and treatment.

Keywords **:** Cracked tooth/teeth diagnosis, Cracked tooth prognosis, Quantitative light-induced fluorescence technology(QLF), Root canal treatment

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I. Introduction

A cracked tooth indicates a crack that extends from the occlusal surface of the tooth towards the root, without separating the two segments, and the crack line is typically centrally located and may involve either or both marginal ridges.[1] Histologic study[2] reveals that crack lines serve as niches for bacterial colonization, and biofilms may propagate within them, reaching the pulp tissue and potentially causing symptoms of pulpitis.

Patients with a cracked tooth typically experience sharp pain when biting hard food, acute pain upon release, which is referred to as ‘rebound pain’, or hypersensitivity/sensitivity to cold stimuli. Lynch *et al.*[3] have categorized the causes of cracks into four main groups: '1. restorative procedures,' such as polymerization stress of composite resin and excessive cavity preparation; '2. occlusal factors,' including masticatory force, trauma from occlusion, or parafunctional habits; '3. developmental conditions,'; and '4. miscellaneous factors.'. Multi-factorial causes of cracked teeth accumulate as the human lifespan increases, leading to a growing tendency for an increase in the incidence of cracked teeth.[4] Nevertheless, diagnosis and treatment of cracked teeth still remain challenging due to their complex etiology and often unpredictable prognosis,[5] resulting in inconsistent treatment decisions among practitioners.[6]

A careful history taking and evaluation of the symptoms is important to predict the prognosis of the cracked tooth and the cease of pain upon releasing the pressure is a key factor for diagnosis.[4] Naked-eye examination, staining with dye, transillumination, and a bite test using a cotton roll or a specially designed bite stick to focus the force (e.g., ‘Tooth Slooth’) are recommended methods for locating crack lines and reproducing symptoms.[7,8]

Once a cracked tooth is diagnosed, external or internal splinting of cracked tooth using orthodontic bands, composite resins, or crowns can halt or delay the progression of cracks and relieve symptoms in some cases.[9, 10] However, proper management of a cracked tooth is often challenging, and discomfort may worsen within a year after definitive restorative treatment, or in cases where cracks extend into the pulp, root canal treatment may be

required, and even tooth loss can occur.[11] Since the direct assessment of crack depth is limited, and clinically diagnosing a cracked tooth with varying patients' symptoms is difficult with the possibility of misunderstanding the patients' subjective chief complaints, clinicians may miss opportune diagnosis timings. This can lead to inappropriate treatment plans that often result in root canal treatment after the cementation of final restoration, which in turn results in the occlusal defect on the crown. Quantifying crack line in some way could help predict crack progression and its prognosis, present evidence-based treatment guidelines, and improve clinical efficiency to achieve successful treatment.

Quantitative light-induced fluorescence (QLF) technology detects the red fluorescence of porphyrin, bacterial metabolites, in early carious lesions, dental plaque, and crack lines by irradiating teeth with visible blue light at a wavelength of 405 nm.[12] Recently, the QLF diagnostic device has gained medical technology certification for caries diagnosis,[13, 14] showing potential for early diagnosis of cracked teeth and quantitatively indicating the extent of crack penetration and bacterial invasion.[7, 15]

Using fluorescence image captured by QLF device, the loss of fluorescence (ΔF) is calculated by comparing fluorescence values of sound tooth areas with those of where fluorescence has decreased. The mean value is then used as the representative measure. In a same manner, red fluorescence (ΔR) caused by bacterial metabolites such as porphyrin is quantified by comparison with normal areas as an indicator of bacterial deposition at the lesion site.

To our best knowledge, there is a lack of correlation studies regarding the use of QLF for diagnosing cracked teeth. While it is possible to visually recognize and diagnose cracked teeth using QLF technology,[16] there is a shortage of follow-up studies investigating the correlation between root canal treatment and cracked teeth, which would help predict the prognosis of cracked teeth. As QLF technology evaluates porphyrin from bacteria, and the width of the crack line tends to be proportional to its depth, a high value of ΔR is expected to be related to the width and depth of the crack lines.[17]

The purpose of this paper is to conduct a quantitative evaluation of cracked teeth using QLF and to retrospectively study whether the results can be used to determine prognosis related to root canal treatment of teeth in the future to help establish a treatment plan. The null hypothesis is that there is no significant correlation between the QLF technique analysis values and the potential for the endodontic prognosis of cracked teeth.

II. Materials and Methods

1. Patient Selection

This study was approved by the Institutional Review Board of Gangnam Severance Hospital (approval number: 3-2023-0274). Patients visiting the Department of Conservative Dentistry in Gangnam Severance Dental Hospital who experienced unexplained biting pain, were suspected of having fractured teeth, or had visibly cracked

teeth during checkup or treatment were examined from April 2019 to April 2023. The final treatment results were recorded during follow-up until August 2023, and the minimum follow-up period was 4 months and the maximum was 52 months (average 19.1 months).

- **Inclusion criteria**

Teeth diagnosed and examined for cracks using QLF device at Gangnam Severance Hospital based on the following signs and symptoms

- Patients experiencing repetitive sharp pain when biting, with a visible crack line on the tooth

- Patients having sensitivity to cold stimuli, with a crack line present on the tooth

- **Exclusion criteria**

Teeth with no subsequent dental records after diagnosis

Teeth extracted immediately after diagnosis

Teeth with sign and symptoms of irreversible pulpitis

Teeth diagnosed as pulp necrosis before restorative treatment

Patients who have not completed endodontic treatment after initiation of root canal treatment and for whom further follow-up is unavailable

2. Data Collection

The patients' age, sex, signs and symptoms were noted, as well as the tooth number, type of restoration, pulp vitality, bite test results, percussion test results, crack direction, and periodontal pocket depth.

In order to replicate the symptoms, biting tests were performed using a cotton swab, or a cotton roll, and the result was recorded as +/-, including ‘rebound pain’ also recorded as “+”. In the percussion test, teeth were divided into +/- after tapping teeth with the handle of dental mirror or pincette. Pulp sensitivity was determined using an ice stick or a cotton pellet that was cooled with dental cold spray. The normal responses were recorded as “+”, increased sensitivity or pain was recorded as “++”, lingering pain as “+++”, and the result was recorded as “-” if there was no response.

Diagnosis and localization of causative crack lines were conducted through the use of Qraypen C (AIOBIO, Seoul, Korea). Total 207 teeth of 149 patients were diagnosed as cracked teeth and further follow-up was conducted. Since diagnosed, if restorative treatment, provisional and final crown restoration, or endodontic treatment was performed, treatment date records and duration since diagnosis were calculated. If the tooth was extracted, the date and reason of extraction were recorded. Out of 207 cases, root canal treatment was performed on 44 (21.3%), and 4 (1.9%) teeth were extracted.

3. QLF image Analysis

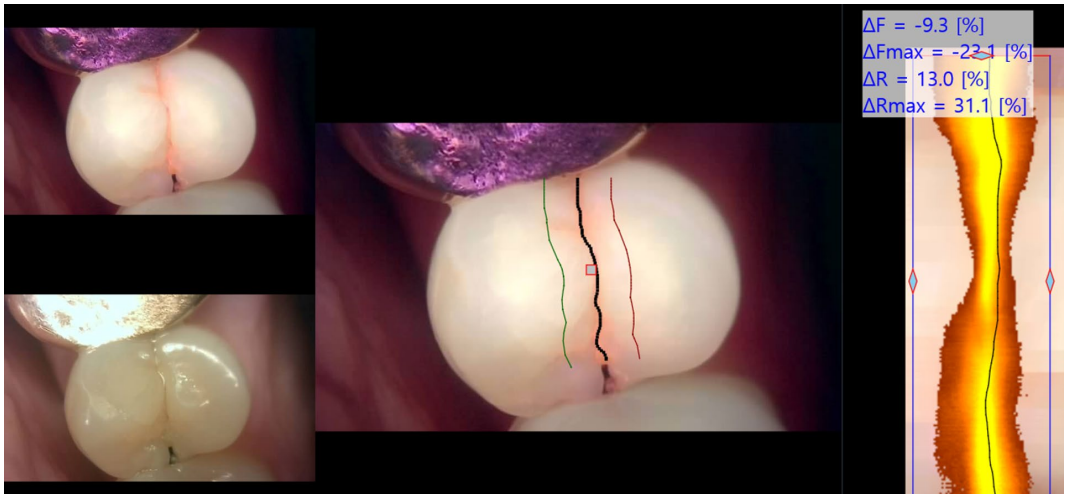


Figure 1. A representative image of a cracked tooth analysis using a prototype software (CrazeLineWizard01 v1.02, AIOBIO).

Photographs taken using the Qraypen C were automatically transferred and saved as an initial step within the Q-ray software v1.45 (AIOBIO) and a specially developed program, CrazeLineWizard01 v1.02 (Inspektor Research Systems BV, Amsterdam, The Netherlands), was used to quantitatively analyze cracks in natural teeth from *in vivo* fluorescence images (at 405 nm excitation with 1280 × 720pixel resolution) (Figure 1).

The program utilized both the original image pixels and the reconstructed ones to compute various parameters. These parameters include ΔF (representing the mean value of the fluorescence change), ΔFmax (indicating the highest value of the fluorescence loss), ΔR

(representing the mean value of the fluorescence change), and ΔRmax (indicating the highest value of ΔR). These parameters were recorded for each tooth. In cases where there were multiple separate crack lines, each crack line was examined separately, and the highest parameter value from each was selected. The analysis of all the images were carried out by one post-graduate resident with 4-year clinical experience. Following the completion of the QLF analysis, the data were decoded for statistical analysis.

4. Statistical Analysis

SAS version 9.4 (SAS Institute, Cary, NC, USA) was used for the statistical analysis. Independent two sample t-test, Analysis of variance (ANOVA), Pearson's correlation coefficient test and post-hoc analysis were employed to investigate the correlations between ΔF, ΔF_{max}, ΔR, and ΔR_{max}, and patients' age, sex, symptoms upon percussion and biting, type of restorations, treatment type, and observation period until endodontic treatment. Univariable logistic regression and area under the curve (AUC) comparison were used to ascertain which QLF value is most significantly associated with RCT. A p value $< .05$ was considered statistically significant.

III. Results

1. Descriptive Analysis

A total of 207 teeth from 149 patients (71 males, 78 females) were diagnosed with cracked teeth and included in the study for analysis. The average age of patients was 57.3 years. Molars were the most abundant with 178 (86.0%), followed by premolars with 27 (13.0%), and there were 2 incisors (1.0%) (Table 1).

Table 1. Descriptions of cracked teeth included in this study (n = 207).

		Sex		Age							
		Male	Female	21-30	31-40	41-50	51-60	61-70	71-80	81-90	(%)
Maxilla											
	Incisor	0	1	0	0	0	0	1	0	0	0.5%
	Premolar	11	12	0	1	3	12	4	3	0	11.1%
	Molar	43	50	1	6	19	29	21	12	5	44.9%
Mandible											
	Incisor	1	0	0	0	0	0	0	1	0	0.5%
	Premolar	1	3	0	0	0	3	0	1	0	1.9%
	Molar	37	48	1	9	19	35	11	7	3	41.1%

One hundred twenty-six teeth experienced pain when biting or releasing bite force at the clinic, symptoms were not duplicated during the bite test for 27 teeth, and there was no recorded bite test for 54 teeth. Thirty-six teeth had pain during the percussion test, 101 teeth showed no response, and percussion test records were missing for 70 teeth. For the pulp sensibility test, 90 teeth showed a normal response to cold stimulus, 36 teeth were sensitive, and 82 cases had no record of the cold test.

Out of a total 207 teeth, 117 had no history of restoration, 17 teeth had amalgam fillings, 51 teeth were restored with gold inlays/onlays, and composite resin restorations were performed on 20 teeth. Ceramic restorations were carried out in 2 cases. The most predominant crack direction was mesio-distal (52.2%, 108 teeth), followed by both mesio-distal and bucco-lingual (20.8%, 43 teeth), bucco-lingual (18.4%, 38 teeth), and cusp fracture (8.7%, 18 cases).

During the follow-up period, 159 teeth received restorative treatment (83 cases of crown and 22 cases of composite resin restoration and 54 cases with no treatment) and 44 teeth underwent root canal treatment (39 cases before the final crown placement and 5 cases after the final cementation). RCT was conducted when symptoms are not relieved or deteriorated during the follow-up. Teeth with irreversible pulpitis or pulp necrosis on the time of diagnosis were excluded from this study. Four teeth were extracted and the details of the extracted teeth are described in Table 2.

Table 2. Descriptions of 4 cases leading to extraction based on a diagnosis of a cracked tooth.

			PI			Qray				Follow-up period			
No.	Age	Tooth	Per	Bite	Crack	ΔF	Fmax	ΔR	Rmax	Temp. cr	RCT	Ext	Note
1	62	#15	+	+	M-D	-8.4	-10.4	13.2	25.7	-	0	23	subgingival fracture margin -palatal cusp
2	67	#25	+	+	M-D	-10	-26.2	13	33	14	30	113	mob(+++) with distal bone loss, pus discharge after RCT
3	61	#26	+	+	M-D	-14.6	-25	15.2	29	-	133	164	subgingival fracture margin -palatal cusp
4	41	#47	-	+	M-D & B-L	-6.8	-41.8	8.5	13.9	34	23	115	buccal swelling subside with full probing depth

2. QLF image Analysis

Table 3 presents the QLF image values of ΔF, ΔFmax, ΔR, and ΔRmax of different treatment types including restorative treatment, root canal treatment (RCT), or extraction. All of the four QLF values (ΔF, ΔFmax, ΔR, and ΔRmax) had significant differences between restorative treatment group and RCT group ($p < .0001$). Extraction group showed no significant differences with the other groups ($p > .05$), except for ΔFmax of extraction group and that of Restorative Tx group ($p < .05$).

Table 3. QLF image analysis values per treatment type; Mean value ± Standard Deviation.

		Restorative Tx (n=159)	RCT (n=44)	Extraction (n=4)	*p* value
QLF analysis	ΔF	-7.66 ± 2.72^{a}	-10.08 ± 3.91^{b}	-9.95 ± 3.36^{ab}	<.0001
	ΔFmax	-14.97 ± 6.85^{a}	-22.02 ± 11.06^{b}	-25.85 ± 12.83^{b}	<.0001
	ΔR	9.64 ± 2.74^{a}	12.54 ± 4.37^{b}	12.48 ± 2.83^{ab}	<.0001
	ΔRmax	17.24 ± 6.98^{a}	26.75 ± 14.77^{b}	25.40 ± 8.23^{ab}	<.0001

Within each row, numbers including same superscript lowercase are not significantly different at $p > .05$ following post-hoc analysis

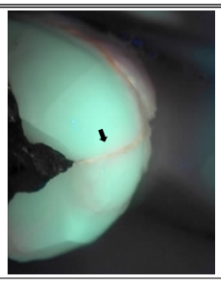
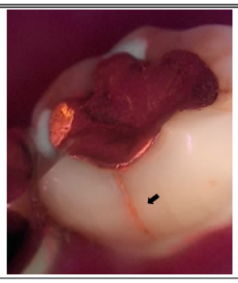
QLF image			
Tooth	#25	#37	#47
ΔF	-3.1	-6.6	-12.3
ΔFmax	-3.1	-11.9	-30.7
ΔR	6.8	14.5	16.1
ΔRmax	9.6	25.4	38.6

Figure 2. Representative fluorescence images (at 405 nm wavelength) of cracked teeth with each QLF value.

The incidence of RCT was presented using a ΔF interval of 5 (Table 4). Among the cracked teeth with a ΔF of less than -15, 80.0% received RCT, whereas 38.89% of teeth had RCT when ΔF was between -15 and -10; 16.95% had RCT when ΔF was between -10 and -5, and only 10.00% of cracked teeth had RCT when their ΔF was higher than -5. The probability of RCT was the highest with ΔF less than -10, of which was significantly different from the other groups (p = .0001). The representative images of the intervals are shown in Figure 2.

Table 4. RCT probability by Q-ray ΔF interval - the number of teeth (%).

	ΔF<-15	-15≤ΔF<-10	-10≤ΔF<-5	-5≤ΔF
RCT				
Yes	4(80.00)^a	21(38.89)^a	20(16.95)^b	3(10.00)^b
No	1(20.00)	33(61.11)	98(83.05)	27(90.00)
Total	5(100)	54(100)	118(100)	30(100)

Within each row, numbers including same superscript lowercase are not significantly different at p > .05 *following* post-hoc analysis

In the case of ΔFmax values (Table 5), out of 43 cracked teeth with a ΔFmax value higher than -10, 16.28% underwent RCT. When ΔFmax was between -20 and -10, 15 out of 104 cases (14.42%) received RCT. For ΔFmax values between -30 and -20, 37.78% had RCT, and the probability of requiring RCT exceeded 50% when ΔFmax was less than -30, with 60.00% undergoing the treatment.

Table 5. RCT probability by Q-ray ΔFmax interval - the number of teeth (%).

	ΔFmax<-30	-30≤ΔFmax<-20	-20≤ΔFmax<-10	-10≤ΔFmax
RCT				
Yes	9(60.00)^a	17(37.78)^a	15(14.42)^b	7(16.28)^b
No	6(40.00)	28(62.22)	89(85.58)	36(83.72)
Total	15(100)	45(100)	104(100)	43(100)

Within each row, numbers including same superscript lowercase are not significantly different at p > .05 *following* post-hoc analysis

When the value of ΔR was above 15, 61.11% (11 out of 18 cases) received endodontic treatment. For cracked teeth with ΔR between 10 and 15, 26.51% underwent endodontic treatment, and 13.33% had RCT when ΔR was below 10. The differences between the three

groups higher than 15 and the other two groups were statistically significant ($p < .05$) (Table 6).

Table 6. RCT probability by Q-ray ΔR interval - the number of teeth (%).

	ΔR<10	10≤ΔR<15	15≤ΔR
RCT			
Yes	$14(13.33)^a$	$22(26.51)^a$	$11(61.11)^b$
No	91(86.67)	61(73.49)	7(38.89)
Total	105(100)	83(100)	18(100)

Within each row, numbers including same superscript lowercase are not significantly different at $p > .05$ following post-hoc analysis

When the ΔRmax of cracked teeth was above 40, 100% (8 cases) received endodontic treatment. The probability of cracked teeth requiring RCT with a ΔRmax between 30 and 40 was 41.18%, while for those with an ΔRmax between 20 and 30, it was 31.48%. Finally, when the ΔRmax was below 20, 11.81% (15 out of 127 cases) received endodontic treatment. The differences among the groups with ΔRmax below 20, between 20 and 40, and above 40 were statistically significant ($p < .05$) (Table 7).

Table 7. RCT probability by Q-ray ΔRmax interval - the number of teeth (%).

	ΔRmax<20	20≤ΔRmax<30	30≤ΔRmax<40	40≤ΔRmax
RCT				
Yes	15(11.81)^a	17(31.48)^b	7(41.18)^b	8(100.00)^c
No	112(88.19)	37(68.52)	10(58.82)	0(0.00)
Total	127(100)	54(100)	17(100)	8(100)

Within each row, numbers with same superscript lowercase letter are not significantly different at $p > .05$

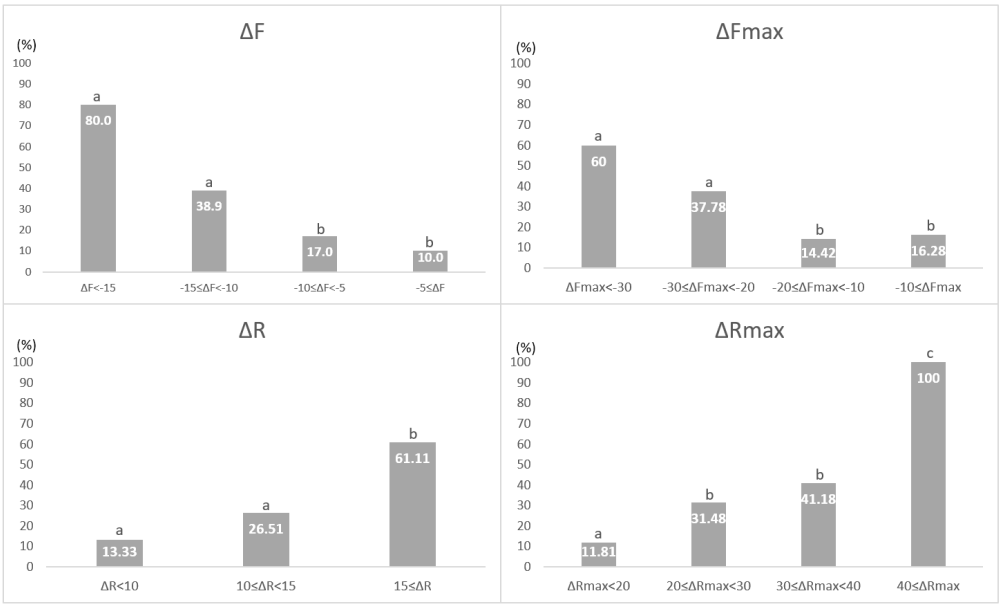


Figure 3. RCT probability (%) by Q-ray values (ΔF, ΔFmax, ΔR and ΔRmax) interval.

Numbers with same lowercase letter are not significantly different at $p > .05$

Univariable logistic regression and AUC comparison test revealed that all four QLF values (ΔF, ΔFmax, ΔR and ΔRmax) were significantly related to the probability of RCT (p

< .0001). The comparison of the four AUCs and the bootstrap method exhibited no significant differences in the significance levels among the QLF values (Figure 4).

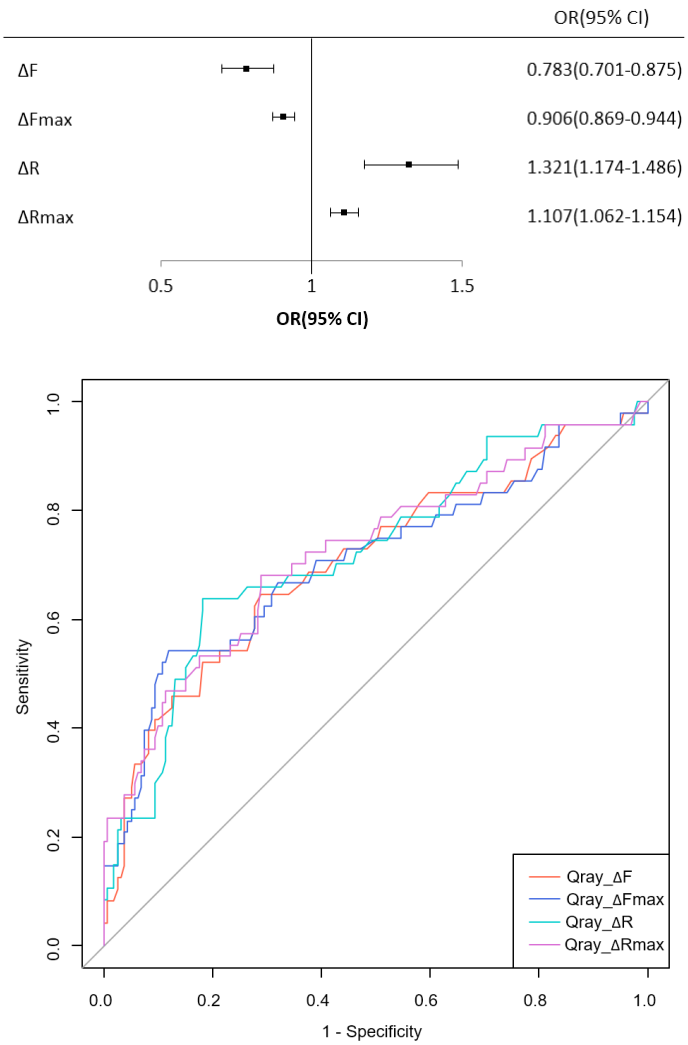


Figure 4. Association of QLF values and the probability of RCT as a result of univariable logistic regression (p < .0001).

This study also investigated the follow-up period until the initiation of RCT from the time of diagnosis. Two asymptomatic teeth, with no pain on percussion and biting at the time of diagnosis, and one tooth with crack line confined to one cusp only, were statistically identified as outliers (follow-up: 696 days, 266 days, and 1031 days, respectively) and were excluded from the calculations. Additionally, the 15 cases that underwent root canal treatment on the same day as the diagnosis were also excluded.

No distinct proportional relationship was observed between the four QLF values and the follow-up period until the initiation of RCT (Figure 5). To facilitate the interpretation of the results, arbitrary intervals were established. The findings indicated that symptomatic cracked teeth with specific QLF values exhibited varying timelines for initiating RCT (Table 8), as illustrated in Figure 6 with a boxplot of the observation time. As ΔF and $\Delta Fmax$ decrease, and $\Delta Rmax$ increase, there is a tendency for a reduction in the observation time, with higher probability of requiring RCT. In particular, for the cases where $\Delta F < -10$, $\Delta Fmax < -30$, $\Delta R > 15$, or $\Delta Rmax > 30$, the interquartile range until the initiation of RCT was within 2 months.

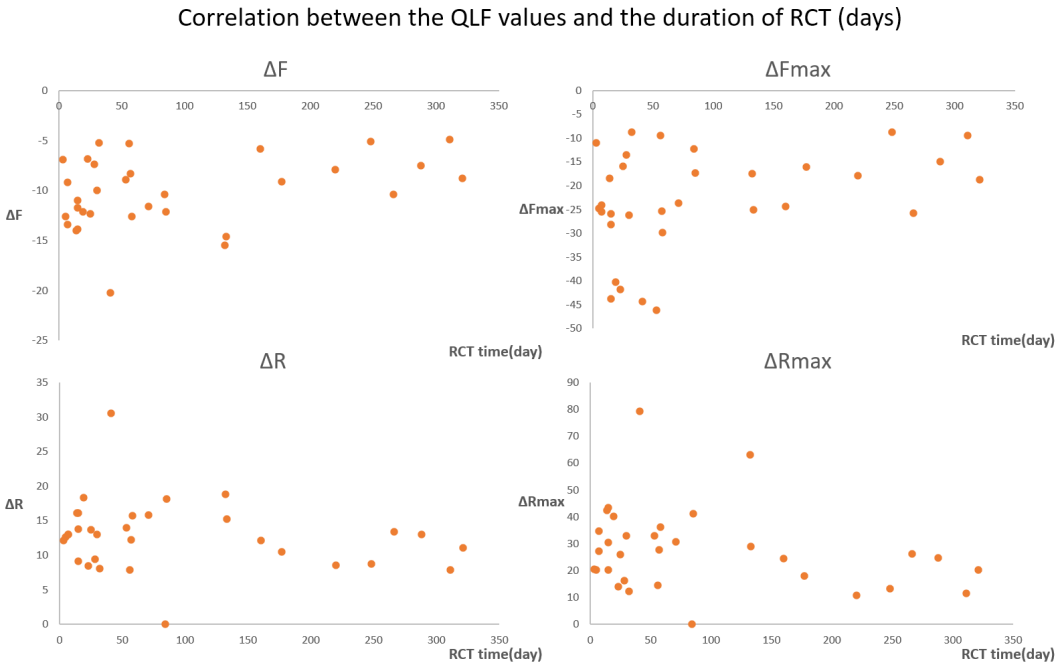


Figure 5. Correlation between the follow-up period (days) until the initiation of RCT and QLF values.

Table 8. Follow-up period (days) until the initiation of RCT ($p > .05$).

	ΔF<-10	-10<ΔF<-5	-5<ΔF
Median	33	57	311
IQR	15-85	29-241	-
Range	5-133	3-321	-
Mean	62	157	311

	ΔFmax<-30	-30<ΔFmax<-20	-20<ΔFmax<-10	-10<ΔFmax
Median	23	44	85	248
IQR	17-47	9-118	25-220	44-557
Range	15-53	5-266	3-321	32-802
Mean	30	69	126	290

	ΔR<10	10<ΔR<15	15<ΔR
Median	56	42	58
IQR	26-280	7-199	17-109
Range	15-311	3-321	14-133
Mean	193	101	63

	ΔRmax<20	20<ΔRmax<30	30<ΔRmax<40	40<Δrmax
Median	177	57	42	30
IQR	30-280	7-266	13-61	15-97
Range	23-311	3-321	7-71	14-132
Mean	211	116	39	51

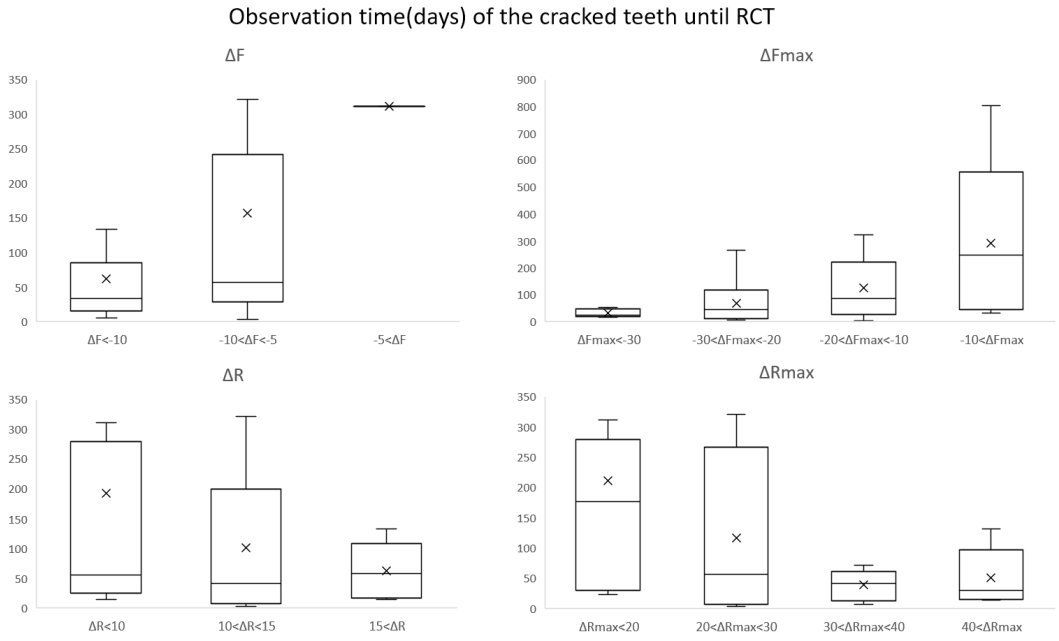


Figure 6. Follow-up period (days) until the initiation of RCT (p > .05) (×: average).

IV. Discussion

This study explores the relationship between QLF analysis values and the treatment outcomes of cracked teeth. Notably, significant differences in QLF analysis values were observed based on the type of treatment administered. Out of the 207 examined cracked teeth, 48 cases (23.2%) required RCT. Cracked teeth with $\Delta F < -10$, $\Delta Fmax < -30$, $\Delta R > 15$, or $\Delta Rmax > 30$ showed a higher probability of requiring RCT within 2 months. Most of the cracked teeth (70%) had temporary crown during the follow up period, and some of them (12%) had composite resin restoration before RCT. Considering the close relationship between the QLF values and RCT, it is advisable to monitor the tooth closely for a sufficient period before proceeding with the final restoration.

According to Wu et al.,[18] 29.1% (58/199) of cracked teeth with reversible pulpitis had pulpal complications, including 38 out of those 58 teeth developing irreversible pulpitis after approximately 1.2 years and 20 of those 58 teeth with necrotic pulp after approximately 2 years. According to Wu's findings, cracked teeth without full-coverage crowns faced higher risks of developing pulpal complications. Additionally, Wu observed that male patients experienced pulpal complications more frequently than female patients (odds ratio = 1.96, $p = .056$), while this study reported 21.3% (44/207) of cracked teeth requiring RCT, showing male patients with a 35.2% (25/71) probability and female patients with a 29.5% (23/78) probability of requiring RCT (odds ratio = 1.30, $p = .455$). Similar to Wu’s study where cracked teeth with a crown showed higher risks of pulpal complications,

this study found that the RCT probability was 27.6% (29/105) for cracked teeth without a crown, and 18.6% (19/102) for cracked teeth with a crown (odds ratio = 1.67, p = .125).

Krell and Rivera[19] also reported that 21.3% (27/127) of cracked teeth with reversible pulpitis required RCT within a 6-month period due to irreversible pulpitis (21/27) and pulp necrosis (6/27), which is comparable to the findings of this study (21.3%) within an average 120-day follow-up. They found that especially 20% of cases required RCT within a 6-month period when either marginal ridge is involved. In this study, 23.6% (37/157) required RCT within 144 days when the crack line involved either marginal ridge.

Other clinical characteristics of cracked teeth that required endodontic treatment include pain on percussion,[10] the crack located on the distal marginal ridge,[19] and deep periodontal probing depth corresponding to the crack.[20] Sensibility tests to cold stimuli are useful tools for evaluating pulp status, but none of them can clearly suggest or solely ensure the possibility of pulpal complications. This explains the necessity of a reliable diagnostic tool to be investigated for clinical consensus.

When treating cracked teeth, interim procedures such as bidirectional splinting[10] and pulp treatment using sedative lining[21] might allow the pulp tissue to resist and repair from bacterial invasion.[18, 19] The bacterial invasion along the crack lines into the pulp chamber causes irreversible pulpitis or pulp necrosis, necessitating RCT. Ricucci *et al* observed biofilm structures colonizing dentinal tubules surrounding the crack line, and the coronal pulp of symptomatic teeth showed severe inflammatory reactions with microabscesses.[2]

Based on the principles of the QLF technology, which detects red fluorescence, the ΔR and ΔRmax values indicate the extent of bacterial invasion in the crack space near the pulp, providing insights into the probability RCT for cracked teeth.

In this study, cracked teeth with ΔR > 15 or ΔRmax > 30 showed high tendency of initiating RCT within 60 days since diagnosis, and ΔRmax seems to have a more discriminative power than ΔR in the point of follow-up period (Table 8). This coincides with the previous study[22] showing signs of pulp tissue repair in 30 days from an inflammatory pulpal state. Also, based on the distribution observed in this study (Figure 5), higher QLF values didn't necessarily mean a shorter follow-up period until the initiation of RCT. Rather than the magnitude of the values, the interpretation should be that exceeding certain intervals, as referenced in Table 8, increases the likelihood of experiencing RCT for cracked teeth. Furthermore, in this experiment, since the follow-up period varied for each tooth, it should be considered that even if RCT was not performed at the time of analysis, RCT may have been performed after a longer period of time.

A systematic review and meta-analysis[23] reported an overall 84.1% survival rate of endodontically treated cracked teeth at the end of 60 months. No pre-operative factors, including gender, dental arch, type of tooth, crack direction and extension, terminal abutment, and initial pulpal diagnosis were significant. However, teeth with a single crack line and a crack line confined to crown without radicular extension were less likely to be extracted. Teeth as terminal abutments or those with probing depth > 3 mm exhibited a higher risk of extraction. Still, an 84.1% 60-month survival rate is reasonably high,

supporting the idea that cracked teeth are salvageable and worth treating rather than extraction at first glance.

In this study, four cases were extracted (one after RCT and three during RCT) (Table 2). Two cases had subgingival unrestorable crown fractures of the palatal cusp, which were not restored with a provisional crown before initiating RCT. Case No.4 exhibited full probing depth at the pre-operative stage, had buccal swelling subside during RCT, and was finally extracted, consistent with the results of meta-analysis.[23] In the case of No.2, which displayed vertical movement with distal bone loss and pus discharge after RCT, vertical root fracture (VRF) was suspected.

This study acknowledges certain limitations. QLF images were taken from various distances and angles from the interested tooth using Qraypen C. Also, when analyzing QLF images, the criteria for dividing the analysis segments and cutoff values were arbitrarily set with consideration for the range of raw data and the sample size, using an F value of 5 and an R value of 10. However, this decision lacks a solid rationale. Furthermore, as a retrospective study, one limitation is that not all teeth followed a consistent protocol for the treatment of crack tooth syndrome. While most procedures were consistent, occasional variations included instances where temporary restorations were omitted before initiating root canal treatment, and the criteria for tooth extraction could vary depending on the practitioner. Further prospective research with a consistent treatment protocol is warranted to address these limitations and to refine the application of QLF in clinical settings.

Nevertheless, this study contributes to establishing quantitative guidelines for understanding the cracked teeth diagnosis and treatment of cracked teeth using QLF technology. Previous studies were limited to evaluating only the presence or absence of the cracks without measuring their extent. This study emphasizes the potential of QLF technology for early diagnosis of the cracked teeth and the formulation of evidence-based treatment guidelines regarding the probability of RCT and its prognosis with an adequate follow-up period.

V. Conclusion

1. Significant differences were observed in QLF analysis values between cracked teeth requiring restorative treatment versus RCT.

2. Teeth with lower fluorescence loss ($\Delta F < -10$, $\Delta Fmax < -30$) and higher red fluorescence values ($\Delta R > 15$, $\Delta Rmax > 30$) exhibited a higher probability of requiring RCT within 2 months.

3. The ΔR and $\Delta Rmax$ parameters, indicating bacterial invasion extent, were particularly useful in predicting RCT need.

4. The QLF technique shows promise as a valuable diagnostic tool for evaluating cracked teeth in predicting the possibility of RCT. While further prospective studies with consistent treatment protocols are warranted, the findings of this study suggest that the QLF analysis

can be a valuable adjunct in the diagnosis and management of cracked teeth, contributing to improved clinical decision-making and treatment outcomes.

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Abstract (IN KOREAN)

정량광형광기술을 이용한 균열 치아의 진단과 근관치료 가능성에 관한 후향적 연구

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균열 치아는 복잡한 원인과 종종 예측하기 어려운 예후로 인해 진단과 치료에 어려움이 있다. 정량광형광기술(QLF)은 박테리아 대사산물인 포르피린에 의해 발생하는 적색 형광을 감지하여 균열 치아의 진단 및 정량화 가능성을 보여준다. 이 후향적 연구의 목적은 정량광형광기술의 균열 치아 진단 및 근관치료 예후 예측 가능성을 알아보는 것이다.

QLF 는 자연광 이미지와 405nm 파장의 형광 이미지를 비교하여 균열선의 형광소실도 (ΔF), 최대 형광소실도 (ΔFmax) 및 적색형광도 (ΔR), 최대 적색형광도(ΔRmax)를 분석하는 기술이다.

2019 년 4 월부터 2023 년 4 월까지 강남세브란스병원에서 진단된 149 명 환자의 207 개 균열 치아가 포함되었으며, 연령, 성별, 타진/감응도/교합 검사 및 균열 방향 등의 임상적인 특징과 QLF 값의 상관관계를 통계 분석하였다.

추적 기간 (평균 19.1 개월)동안 207 개 균열 치아 중 44 개 (21.3%)에서 RCT 를 시행했고 4 개 (1.9%)는 발치되었고, QLF 값은 수복 치료와 RCT 치아 간 유의한 차이를 보였다 ($p < .0001$). ΔF < -10, ΔFmax < -30, ΔR > 15 또는 ΔRmax > 30 인 균열 치아의 RCT 받은 비율은 약 60%였으며 ($p < .05$), RCT 시작 시기도 다양했다. 로지스틱 회귀분석에서 4 가지 QLF 분석값은 모두 RCT 확률과 유의한 상관관계가 있었다($p < .0001$). 또한 ΔR > 15 또는 ΔRmax > 30 인 균열 치아는 진단 후 60 일 이내에 RCT 확률이 각각 61.1%, 60.0%로 나타났다.

이 연구는 균열 치아의 최종 수복 전 충분한 경과 관찰 기간의 중요성을 강조하며, QLF 기술을 이용한 균열 치아의 정량적 진단과 근거에 기반한 치료 계획 수립 가능성을 보여주었다. 다만 표준화된 프로토콜을 갖춘 전향적 연구를 통해 QLF 의 임상 적용을 검증하고 균열 치아 진단 및 치료를 위한 정량적 가이드라인을 수립할 필요가 있을 것이다.