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Effects of Procedural Errors on Root Canal Treatment Outcomes: A Retrospective Cohort Study of Cases Treated by Sixth-year Dental Students

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ABSTRACT

Objective: This study assessed the effects of various types of procedural errors arising from root canal instrumentation on initial root canal treatment outcomes.

Methods: This retrospective cohort study analysed data from sixth-year dental students performing initial root canal treatment on mature permanent molars between 2015 and 2019. Treatment records and radiographic images were reviewed to identify procedural errors during root canal instrumentation and other potential confounding factors affecting treatment outcomes. Subsequently, uni- and multivariate logistic regression analyses were performed to identify predictors of treatment outcomes.

Results: A total of 142 teeth (343 roots) met the inclusion criteria, with an average follow-up period of 35.84±16.72 months. According to stringent assessment criteria, overall healing rates were 72.5% for the teeth (103 of 142) and 80.5% for the roots (276 of 343). Multivariate logistic regression analysis revealed that among the procedural errors considered, only errors related to under-instrumentation (root canal deviation and lateral perforation) were significant predictors of treatment outcomes ($p=0.002$).

Conclusion: Root canal treatment outcomes are significantly influenced by procedural errors, particularly those affecting the root canal preparation length. Procedural errors related to under-instrumentation can compromise root canal disinfection and increase the risk of post-treatment disease by up to eightfold.

Keywords: Apical periodontitis, procedural errors, root canal preparation, root canal treatment, treatment outcome

HIGHLIGHTS

- Procedural errors impact root canal outcomes, with under-instrumentation posing the highest risk.
- In this retrospective study, healing rates were 72.5% for teeth and 80.5% for roots, with a mean follow-up duration of 35.84 months.
- Errors related to under-instrumentation increase post-treatment disease risk by up to eightfold.

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INTRODUCTION

Root canal instrumentation is a crucial step in root canal treatment, as it involves the removal of infected tissue, bacterial biofilm, and their toxic by-products. It also creates space for antimicrobial irrigants, which enhance the cleaning of untreated root canal walls and address anatomical irregularities. Additionally, instrumentation shapes the canal to accommodate the available obturation material and technique, thereby establishing conditions that support the preservation of healthy apical tissues or promote the healing of apical periodontitis (1, 2). It is widely recognised that optimal root canal preparation should result in a continuous, tapered shape that closely follows the original root canal anatomy, free from procedural errors (3).

However, due to various factors, including the complexity of root canal anatomy, accessibility, instrument flexibility, and operator experience, procedural errors may arise during root canal preparation (4). These errors are typically categorised as root perforation, instrument separation, and uncontrolled canal shaping (5). It is important to note that these errors can vary not only between categories but also within the same category. For instance, variability can occur in the location and size of perforations, in the ability to regain apical patency following instrument fracture, or in the effects of uncontrolled canal shaping on the length of root canal instrumentation. Consequently, these errors can have distinct and varying impacts on the overall success of root canal treatment.

Current clinical studies demonstrated that root perforation significantly reduces the healing rate of initial root canal treatment (5, 6). This is because root perforation causes injury and inflammation to the adjacent periodontium, particularly when it occurs near the alveolar crestal bone, as usually observed in cases with furcal and strip perforations. These conditions can lead to epithelial downgrowth and attachment loss, potentially resulting in tooth loss if not properly managed (7–10). In cases of instrument fracture, clinical studies demonstrated that the inability to regain apical patency in teeth with preoperative radiolucency significantly decreases the healing rate of initial root canal treatment (5, 6, 11). This is attributed to the fact that fractured instrument inside the root canal could make further disinfection of the apical portion of the root canal beyond the fracture site rather challenging (6, 12).

Procedural errors within the category of uncontrolled canal shaping remain insufficiently studied, with only indirect histopathological and *in vitro* studies suggesting potential trends that may impact the success of root canal treatment. For instance, root canal deviation may result in the persistence of bacteria and debris in the untreated apical portion of the root canal (13), while apical perforation may facilitate the migration of bacteria beyond the root apex, potentially compromising the prognosis (14). However, to date, no well-controlled clinical studies have been conducted to examine procedural errors within this category.

Therefore, this study aimed to assess the effect of various procedural errors during root canal instrumentation, performed by sixth-year dental students using stainless-steel hand files, on the outcome of initial root canal treatment. The null hypothesis was that each type of error had no effect on treatment outcomes.

MATERIALS AND METHODS

Study Population

The Institutional Review Board of the Faculty of Dentistry/ Faculty of Pharmacy, Mahidol University, approved the study protocol (MU-DT/PY-IRB 2020/017.1603). The study was also conducted in accordance with the Declaration of Helsinki. The study population comprised patients who underwent initial root canal treatment in mature permanent molars by sixth-year dental students at the Faculty of Dentistry between 2015 and 2019, using stainless steel hand files for root canal instrumentation. This retrospective study adhered to the "Strengthening the Reporting of Observational Studies in Epidemiology" (STROBE) statement and checklist and the "Preferred Reporting Items for Observational Studies in Endodontics" (PROBE) 2023 guidelines.

Case Selection

This study included patients with a follow-up period of at least 1 year and a comprehensive endodontic chart, including pretreatment information, intraoperative records, and follow-up visit documentation. The chart also needed to contain a complete set of radiographs, including preoperative, working length, master apical file (MAF), main gutta-percha cone, postoperative, and follow-up radiographs. Exclusion criteria included patients with poor-quality radiographs, teeth extracted for reasons unrelated to endodontic disease, or those lacking periapical status information at extraction.

Treatment Protocol

All procedures were conducted under rubber dam isolation conditions. The tooth and rubber dam (M Dent, Bangkok, Thailand) were disinfected sequentially with 5% iodine tincture, followed by 70% ethyl alcohol. Any deteriorated dental restorations or carious lesions were removed, and the teeth were subsequently restored using a resin composite (Z250; 3M ESPE, Seefeld, Germany). After access cavity preparation, the root canal orifices were located and explored using precurved size 8 or 10 stainless-steel hand files (Dentsply Maillefer, Ballaigues, Switzerland) with a watch-winding motion.

Root canal preparation protocol was systematic, beginning with coronal flaring, followed by apical preparation and complete shaping. Coronal portions of the root canals were enlarged using size 2 or 3 Gate-Glidden burs (Dentsply Maillefer, Ballaigues, Switzerland) or size 40 – 60 K- files using the crown-down technique. Working length was determined using the initial apical file (IAF), electronic apex locators (EAL; Root ZX, J. Morita USA Inc., Irvine, California, United States), and periapical radiographs. Apical preparation continued sequentially using hand files at the working length until the root canal size reached the desired MAF (which is at least 3 sizes larger than IAF, or at least size 30), followed by a sequential 1 mm step-back preparation for complete shaping. Subsequently, the length and direction of the root canal instrumentation were verified using MAF, EAL, and periapical radiographs.

All root canals were frequently irrigated with 2.5% sodium hypochlorite solution (M Dent, Bangkok, Thailand) using a gauge No. 25 needle and a syringe. Calcium hydroxide (M Dent, Bangkok, Thailand) was used as an intracanal medicament between treatment sessions, and the access cavity was sealed with temporary filling materials, including Caviton® (GC Corporation, Tokyo, Japan) and IRM® (Dentsply Maillefer, Ballaigues, Switzerland).

Root canal filling was initiated after the patient was asymptomatic. Before root canal filling, the canals were irrigated with 3 mL of 17% ethylenediaminetetraacetic acid (M Dent, Bangkok, Thailand) for 1 minute, followed by 2.5% sodium hypochlorite to remove the smear layer. Gutta-percha (Dentsply Maillefer, Ballaigues, Switzerland) and zinc oxide eugenol sealer (M Dent, Bangkok, Thailand) were used to obturate the root canals using the lateral compaction technique. The root canal orifices were sealed with glass ionomer cement (Fuji VII; GC Corporation, Tokyo, Japan), and the access cavity was restored using resin composite filling (Z250; 3M ESPE, Seefeld, Germany) as an intermediate restoration.

Data Collection

Data were acquired from treatment records and radiographs in each patient's endodontic chart, including demographic characteristics (age, sex, and systemic disease) and preoperative clinical assessments (presence of cracks, clinical signs and symptoms, periodontal pocket formation, sinus tract opening, and preoperative radiolucency), intraoperative details (including number of visits, procedural errors, and quality of root canal fillings), and postoperative follow-up data (clinical findings similar to the preoperative assessments).

Radiographic Assessment

Conventional radiographs were digitised using a scanner (HP Scan G4010, HP Inc., Palo Alto, California, United States) and evaluated by a single examiner (S.T.) using ImageJ software (National Institutes of Health, Bethesda, Maryland, United States). Radiographic evaluation was performed by a single reviewer who was calibrated with a certified endodontist before the assessment process began. The examiner received training from a certified endodontist using a set of 30 radiographs. Subsequently, the examiner reviewed the same set of radiographs twice, with a 2-week interval between reviews. Inter- and intra-examiner agreement in radiographic evaluations was assessed using Cohen's kappa coefficients. Notably, prior to the study, there was nearly perfect agreement between examiners and the certified endodontist, as well as within the same examiner (k=0.81–0.99, reference for nearly perfect agreement).

Detection of Procedural Errors

A comprehensive radiographic assessment was performed after identifying procedural errors in the treatment records, especially ledges that may not have been visible on radiographs. This assessment focused on detecting errors that occurred during root canal instrumentation, starting with a comparison of the lengths and directions of the IAF and MAF. Working length radiographs provided the length and direction of the IAF, representing the full extent of the root canal requiring instrumentation; MAF radiographs indicated the portion of the canal that had been instrumented.

The instrumented length was classified as adequate if the MAF matched the IAF in both length and direction. Over-instrumentation was recorded when the MAF extended in the same direction as the IAF but was longer (with the tip of the MAF closer to or extending beyond the radiographic apex). Under-instrumentation was noted when the MAF deviated in the direction from the IAF. The length of the uninstrumented root canal was also recorded, measured in millimetres, from the point where the MAF deviated from the original canal path.

Subsequently, the radiographs were examined to detect root perforations, indicated by the presence of MAF or root canal filling extending beyond the root, and any broken instrument fragments within the root canal were noted.

Data from these assessments were used to classify procedural errors. The classification criteria were modified from those of Balto et al. (15) and were categorised into four groups. The first group included errors unrelated to the root canal instrumentation length but resulted in altered root canal shape, such as ledge formation and zipping. A ledge was noted if a visible step or irregularity appeared on the root canal wall (Fig. 1a), while zipping was noted when the apical part of the filled root canal appeared elliptical and shifted toward the outer root wall (Fig. 1b, c).

The second group included errors related to under-instrumentation, such as root canal deviation and lateral perforation. A deviation was recorded if the direction of MAF differed from that of the IAF (Fig. 1d, e). Lateral perforation was noted when deviation was observed alongside the extrusion of the misdirected MAF or root canal filling beyond the root (Fig. 1f, g). The third group involved errors associated with over-instrumentation, specifically apical perforation, which was recorded if the MAF was longer than the IAF or if there was extrusion of the root canal filling through the apical foramen (Fig. 1h, i).

The final group consisted of errors with distinct characteristics, including strip perforations and separated instruments. Strip perforation was indicated if extrusion of the root canal filling was observed at the inner root wall (Fig. 1j), and a separated instrument was indicated if a broken instrument was found inside the root canal (Fig. 1k).

Treatment Outcome Assessment

Preoperative and follow-up periapical status were assessed separately based on the presence/absence of periapical radiolucency. The maximum extent of the apical lesion was measured in millimetres.

Treatment outcomes were assessed by analysing preoperative and follow-up data and classified according to Friedman and Mor criteria (16). Treatment outcomes were classified as "healed" when both clinical and radiographic presentations were normal (Fig. 2a–i), "healing" when a reduction in apical radiolucency size was observed alongside normal clinical findings, and "disease" if apical radiolucency emerged or persisted without change, regardless of normal clinical findings, or if clinical signs or symptoms were present despite normal radiographic findings (Fig. 2j–o). This evaluation considered outcomes at the individual root and overall tooth units, with the overall outcome for each tooth determined by the root with the least favourable outcome.

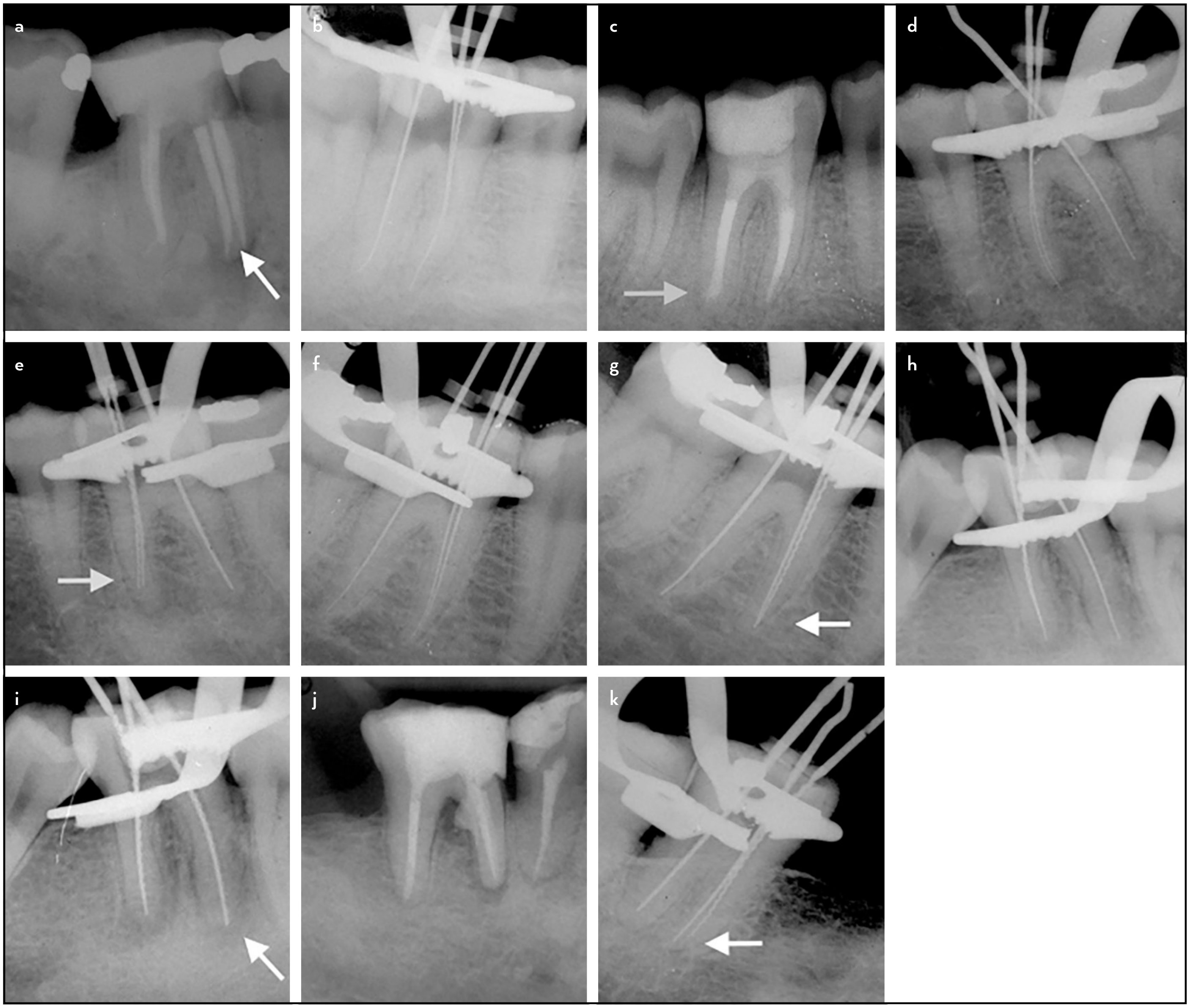

Figure 1. Detection of procedural errors. (a) A ledge was observed in the mesial root of the right mandibular first molar (tooth 46), indicated by a visible step on the canal wall (arrow). (b) Working length determination revealing the original root canal morphology of the right mandibular first molar (tooth 46). (c) Zipping, characterised by an elliptical shape of the apical portion of the distal root (arrow), resulting from apical transportation towards the outer wall of the curved canal, as shown in (b). (d) Original canal morphology of the left mandibular first molar (tooth 36), demonstrated by the IAF during working length determination. (e) Canal deviation was evident in the mesial root (arrow), with the MAF diverging from the IAF, as shown in (d). (f) Working length determination of the right mandibular first molar (tooth 46), showing the initial canal path. (g) Lateral perforation was identified at the mesial root (arrow), as the MAF deviated from the IAF (as seen in f) and extended beyond the root surface. (h) Working length of the left mandibular first molar (tooth 36), demonstrated by the IAF. (i) Apical perforation was evident in the distal root (arrow), marked by the MAF extending beyond the IAF, as shown in (h). (j) Strip perforation in the mesial root of the right mandibular first molar (tooth 46), indicated by extrusion of filling material through the inner root wall. (k) A separated instrument fragment was visible in the mesial root of the right mandibular first molar (tooth 46) (arrow).

IAF: Initial apical file, MAF: Master apical file.

Statistical Analysis

Treatment outcomes based on stringent criteria (normal clinical and radiographic findings) were analysed descriptively for both individual roots and teeth. Predictors of outcomes were identified through uni- and multivariate logistic regression analyses performed at a 5% significance level using Stata software (Stata/SE 17.0, StataCorp LLC, College Station, Texas, USA). Initial analyses covered the entire dataset, followed by sub-analyses of teeth with and without preoperative radiolucency, focusing on the root as the evaluation unit. Logistic regression, with a cluster sandwich estimator for robust standard errors, was used to assess the clustering effect of multiple roots within the same tooth.

RESULTS

Between January 2015 and December 2019, 302 molars underwent root canal treatment from sixth-year dental students. A total of 156 teeth met the inclusion criteria;

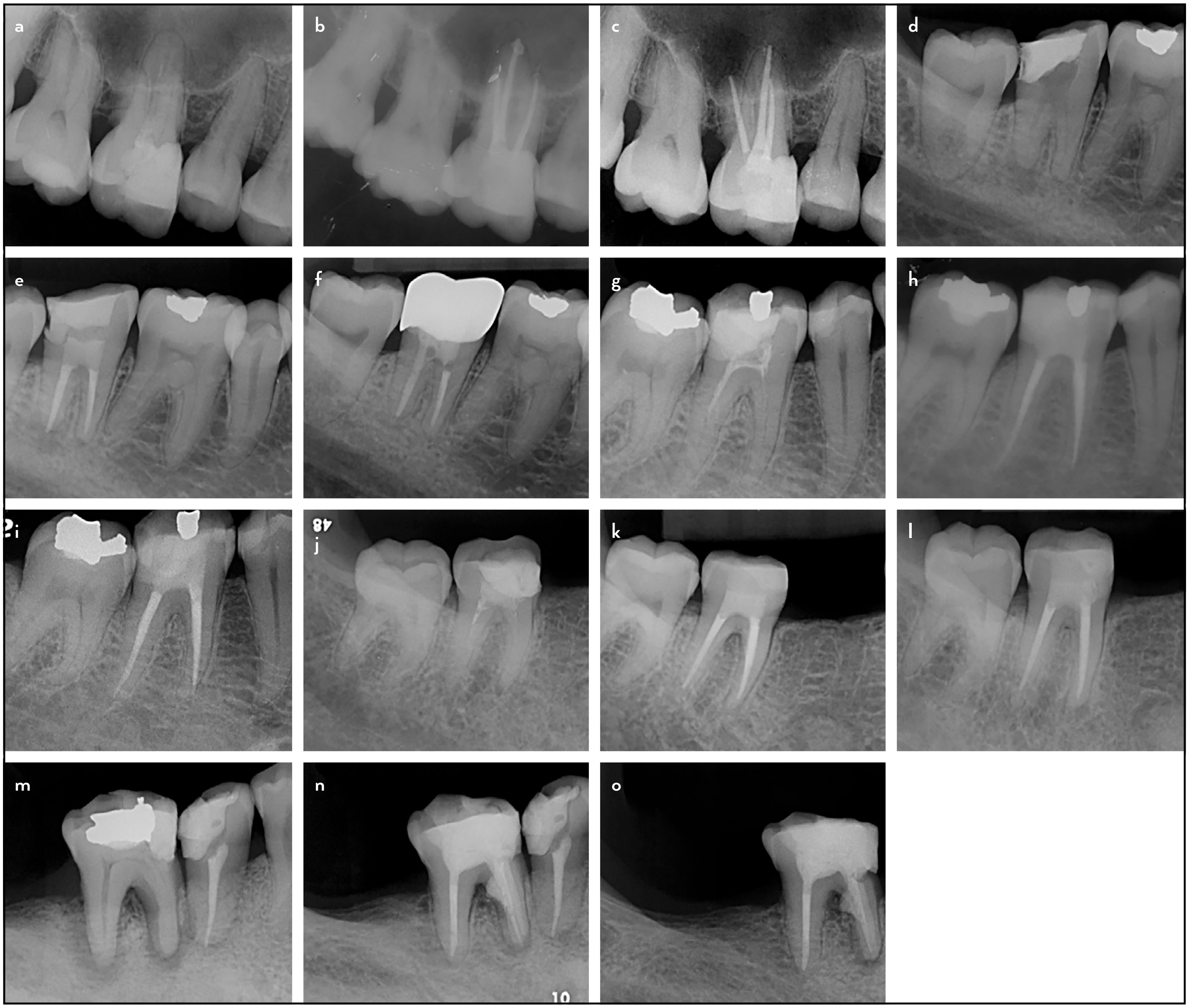

Figure 2. Treatment outcome assessment. (a–c) The preoperative radiograph (a) of the right maxillary first molar (tooth 16) showed normal apical tissues around the palatal root. The postoperative radiograph (b) revealed an apical perforation. At the 2-year follow-up (c), the periapical structures remained normal, and the outcome was classified as "healed." (d–f) The preoperative radiograph (d) of the right mandibular second molar (tooth 47) showed an apical lesion at the distal root. A postoperative radiograph (e) revealed an apical perforation. At the 6-year follow-up (f), the apical tissues appeared normal, and the outcome was classified as "healed." (g–i) The preoperative radiograph (g) of the right mandibular first molar (tooth 46) showed normal apical tissues at the mesial root. A lateral perforation was identified in the postoperative image (h). At the 3-year follow-up (i), the periapical structures remained normal, and the outcome was classified as "healed." (j–l) The preoperative radiograph (j) of the right mandibular second molar (tooth 47) showed an apical lesion at the mesial root. A lateral perforation was evident in the postoperative image (k). At the 4-year follow-up (l), lesion progression resulted in the classification of the outcome as "disease." (m–o) The preoperative radiograph (m) of the right mandibular first molar (tooth 46) revealed a periradicular lesion involving the furcation and apical region of the mesial root. A strip perforation was evident in the postoperative image (n). At the 3-year follow-up (o), persistence of the radiolucency led to the classification of the outcome as "disease".

however, 10 teeth were subsequently excluded due to the unavailability of periapical status information at the time of extraction, and an additional four teeth were excluded because of poor-quality radiographs. Thus, 343 roots from 142 teeth were analysed for treatment outcomes. The mean follow-up duration was 35.84 months, ranging from 12 to 72 months. Based on stringent assessment criteria, the overall healing rates were 72.5% for teeth (103 of 142) and 80.5% for roots (276 of 343).

Univariate analysis identified several significant factors, including patient age, clinical signs and symptoms, preoperative radiolucency, and restoration quality. Among procedural errors, only root canal deviation was significantly associated with treatment outcomes (Table 1). Instances of zipping and instrument separation were rare, occurring in only 1.46% (5/343) and 0.29% (1/343) of roots, respectively, and were not observed in the disease group, limiting their impact assessment. In the multivariate analysis, only procedural errors re-

TABLE 1. Association between potential factors and the healing rate using univariate logistic regression analysis (n=343)

	All	Healed (%)	Disease (%)	Crude OR for disease (95% CI)*	p
Procedural errors					
Ledge					
Absent	320	80.6	19.4	Ref	0.777
Present	23	78.3	21.7	1.156 (0.424, 3.150)	
Deviation					
Absent	318	83.0	17.0	Ref	**<0.001**
Present	25	48.0	52.0	5.296 (2.117, 13.252)	
Lateral perforation					
Absent	332	81.3	18.7	Ref	0.053
Present	11	54.6	45.4	3.629 (0.982, 13.412)	
Apical perforation					
Absent	276	79.3	20.7	Ref	0.291
Present	67	85.1	14.9	0.674 (0.324, 1.402)	
Strip perforation					
Absent	331	81.3	18.7	Ref	0.105
Present	12	58.3	41.7	3.099 (0.788, 12.188)	
Demographic data					
Age (41.11±14.96 years)				0.964 (0.940, 0.989)	**0.005**
Gender					
Female	223	83.0	17.0	Ref	0.256
Male	120	75.8	24.2	1.551 (0.728, 3.308)	
Systemic disease					
Absent	263	82.1	17.9	Ref	0.291
Present	80	75.0	25.0	1.532 (0.694, 3.383)	
Preoperative data					
Crack					
Absent	321	80.4	19.6	Ref	0.910
Present	22	81.8	18.2	0.910 (0.178, 4.641)	
Clinical signs and symptoms**					
Absent	110	70.9	29.1	Ref	**0.032**
Present	233	85.0	15.0	0.431 (0.200, 0.930)	
Periodontal probing depth					
£ 5 mm	330	80.3	19.7	Ref	0.691
> 5 mm	13	84.6	15.4	1.229 (0.446, 3.385)	
Sinus tract opening					
Absent	334	81.1	18.9	Ref	0.074
Present	9	55.6	44.4	3.441 (0.889, 13.323)	
Preoperative radiolucency					
Absent	153	92.8	7.2	Ref	**<0.001**
Present	190	70.5	29.5	5.395 (2.242, 12.984)	
Intraoperative data					
Treatment sessions				1.041 (0.905, 1.197)	0.576
Length of root canal filling***					
Adequate	323	80.5	19.5	Ref	0.959
Inadequate	20	80.0	20.0	1.032 (0.311, 3.418)	
Void of root canal filling					
Absent	332	81.0	19.0	Ref	0.179
Present	11	63.6	36.4	2.44 (0.664, 8.965)	
Follow-up data					
Dental post placement					
Absent	329	79.9	20.1	Ref	0.257
Present	14	92.9	7.1	0.306 (0.040, 2.364)	
Quality of coronal restoration					
Adequate	318	84.0	16.0	Ref	**<0.001**
Inadequate	25	36.0	64.0	9.307 (2.689, 32.217)	

Bold font indicates statistical significance. *: Confidence interval for odds ratios was estimated using robust standard error to allow clustering within the tooth. **: Clinical signs and symptoms comprised tenderness on percussion, tenderness on palpation, or increased tooth mobility. ***: The criterion for evaluating the adequate length of the root canal filling was a distance within 2 mm from the radiographic apex. OR: Odds ratio, CI: Confidence interval

TABLE 2. Significant predictors of treatment outcomes identified using multivariate logistic regression analysis

	Adjusted OR for disease (95% CI)*	p
Procedural errors		
Errors unrelated to instrument length (0=absent, 1=present)	0.997 (0.300, 3.316)	0.996
Errors related to under-instrumentation (0=absent, 1=present)	5.329 (1.895, 14.981)	**0.002**
Error related to over-instrumentation (0=absent, 1=present)	0.767 (0.269, 2.185)	0.620
Error with distinct characteristics (0=absent, 1=present)**	2.122 (0.363, 12.408)	0.404
Demographic data		
Age (year)	0.952 (0.923, 0.981)	**0.001**
Preoperative data		
Clinical signs and symptoms (0=absent, 1=present)	0.327 (0.136, 0.787)	**0.013**
Preoperative radiolucency (0=absent, 1=present)	7.120 (2.457, 20.633)	**<0.001**
Follow-up data		
Quality of restoration (0=adequate, 1=inadequate)	16.542 (2.956, 92.584)	**0.001**

Bold font indicates statistical significance. *: Confidence interval for odds ratios was estimated using robust standard error to allow clustering within the tooth. **: The error with distinct characteristics in this study was strip perforation. OR, odds ratio, CI: Confidence interval

TABLE 3. Significant predictors of treatment outcomes from sub-analysis of teeth with preoperative radiolucency

	Adjusted OR for disease (95% CI)*	p
Procedural errors		
Errors unrelated to instrument length (0=absent, 1=present)	0.479 (0.098, 2.334)	0.362
Errors related to under-instrumentation (0=absent, 1=present)	8.045 (2.094, 30.909)	**0.002**
Error related to over-instrumentation (0=absent, 1=present)	0.925 (0.276, 3.096)	0.899
Error with distinct characteristics (0=absent, 1=present)**	3.261 (0.366, 29.057)	0.290
Demographic data		
Age (year)	0.949 (0.914, 0.984)	**0.005**
Systemic disease (0=absent, 1=present)	4.515 (1.244, 16.379)	**0.022**
Preoperative data		
Clinical signs and symptoms (0=absent, 1=present)	0.259 (0.101, 0.664)	**0.005**
Follow-up data		
Quality of restoration (0=adequate, 1=inadequate)	17.839 (2.698, 117.933)	**0.003**

Bold font indicates statistical significance. *: Confidence interval for odds ratios was estimated using robust standard error to allow clustering within the tooth. **: The error with distinct characteristics in this study was strip perforation. OR: Odds ratio, CI: Confidence interval

lated to under-instrumentation were significant predictors of all procedural errors, with patient age, clinical signs and symptoms, preoperative radiolucency, and restoration quality also identified as predictors (Table 2).

In the sub-analysis of teeth with preoperative radiolucency, errors related to under-instrumentation (odds ratio for disease=8.045, p=0.002), patient age, clinical signs and symptoms, and restoration quality persisted as significant predictors. Systemic disease was also an important predictor (Table 3). Furthermore, when the length of the uninstrumented root canal was included in the sub-analysis, it was also identified as a significant predictor of treatment outcome, with an odds ratio of 4.268 for disease for each 1 mm uninstrumented length (p=0.015).

Conversely, in teeth without preoperative radiolucency, only restoration quality remained a significant predictor (odds ratio for disease=25.871, p=0.006). Neither errors related to under-instrumentation nor the length of the uninstrumented root canal retained their predictive values.

DISCUSSION

Various types of procedural errors occurring during root canal instrumentation exhibit distinct characteristics, potentially leading to diverse impacts on treatment outcomes. This study expands the understanding of these effects, emphasising the importance of preventing errors that significantly deteriorate treatment outcomes. Additionally, clinicians can deliver a more precise prognosis to patients when errors occur.

Given that multiple factors influence root canal treatment outcomes, this study required the collection of other potential prognostic factors for analysis. Our findings indicated that preoperative radiolucency remained a significant predictor, consistent with previous studies (5, 6, 17–19), and its presence reduced the healing rate by up to 20%. Consequently, it was imperative to analyse the data separately for the groups with and without preoperative radiolucency. Coronal restoration quality also emerged as another significant predictor, as restorations with visibly exposed root canal fillings reduced the healing rate by more than 50%. However, the low occurrence rate of inadequate restorations (only 7.3%) rendered similar sub-analyses infeasible.

The null hypothesis that each type of procedural error would have no effect on treatment outcome was rejected. Univariate analysis indicated that root canal deviation was the only considered procedural error significantly associated with treatment outcomes. Lateral perforation resulted in a lower healing rate, although without a significant relationship (p=0.053), likely due to its infrequent occurrence (11/343 roots). As both root canal deviation and lateral perforation result in incomplete root canal preparation, they were categorised together as procedural errors related to under-instrumentation for subsequent analysis. In the multivariate analysis, this category emerged as a significant predictor of treatment outcomes (p=0.002). Bacterial biofilms in unprepared root canal sections likely represent the primary causative factor (13), as supported by the sub-analysis, indicating that these errors specifically affected the treatment outcomes in teeth with preoperative radiolucency (Fig. 2g–l). This finding aligns with that of Ng et al. (6), who observed a 12% decrease in the healing rate for each 1 mm reduction in the apical extent of the MAF.

Previous studies considered short root canal filling to be under-instrumentation; however, their findings were inconsistent despite being from the same researchers (18, 20). This inconsistency may result in short root canal filling being an unreliable indicator of under-instrumentation. For example, debris blockage or gutta-percha cone displacement during obturation can result in a short filling (18, 21). Additionally, evaluating optimal root canal filling length based on a distance within 2 mm from the radiographic apex may be inappropriate, as it does not accurately reflect the correct apical constriction position in each tooth (22, 23). Therefore, evaluating instrument direction changes during the treatment, along with the use of an electronic apex locator, could have enhanced the accuracy of the assessment in this study.

Procedural errors related to over-instrumentation or apical perforations were most frequently encountered in this study. This increased detection rate may have resulted from improved methods, particularly comprehensive radiographic examinations, which allowed for the identification of apical perforations that might have gone undetected in previous studies (15, 21). However, the results of this study indicated that apical perforation had no significant impact on treatment outcomes, likely because this error does not obstruct root canal instrumentation, allowing for effective bacterial biofilm removal (Fig. 2a–f).

Strip perforation, which results from overpreparation in the furcal region of the root canal near the crestal bone, increases the risk of bacterial contamination and attachment loss, ultimately leading to a poor prognosis (7, 8). Although a reduced healing rate was observed in cases of strip perforation, univariate analysis revealed no significant association with treatment outcomes in the present study. This could be attributed to the low incidence rate (12 of 343 roots) and varied management approaches, ranging from immediate repair to delayed repair (up to 370 days). Furthermore, the study lacked information on critical factors, such as perforation size, location, and repair materials (7, 8), limiting the ability to draw definitive conclusions regarding the impact of strip perforation on treatment outcomes.

This retrospective cohort study faced challenges in controlling variables, such as treatment modalities and medications used, alongside potential issues with incomplete data due to inadequately recorded treatments or missing radiographs. However, the selection of patients treated by undergraduate dental students from the dental faculty ensured stringent adherence to treatment protocols and comprehensive data collection, including detailed treatment records and radiographic documentation throughout the treatment duration. The selection of molars treated with stainless steel hand files also facilitated the inclusion of cases with procedural errors in the analysis.

The mean follow-up time of 36 months in the present study ensured an accurate reflection of prognosis, aligning with the recommendation of Ng et al. (24) that a 3-year follow-up period is suitable for stringent outcome evaluations. Nevertheless, limitations persisted due to the inherent two-dimensional nature of periapical radiographs, which restricted visualisation of the buccal or lingual aspects of the root canal and potential overlap with anatomical structures (4). The accuracy of radiographic angulation may have further influenced the assessment of periapical tissues (25, 26).

Further studies may be necessary to examine the impact of procedural errors with low incidence rates, potentially using different study designs or populations to enhance the detection and analysis of these infrequent events. Investigating predictors, such as patient age, systemic disease, and clinical signs and symptoms, would be valuable to establish definitive conclusions in this area where current knowledge remains limited (5, 6, 17, 19).

CONCLUSION

The impact of specific procedural errors on the outcome of root canal treatment is largely determined by their effect on root canal preparation length. This study identified procedural errors related to under-instrumentation as significant predictors. These errors, such as root canal deviation and lateral perforation, impede instrument insertion into the apical portion of the root canal, compromising root canal disinfection and increasing the risk of post-treatment disease by up to eightfold.

Disclosures

Ethics Committee Approval: The study was approved by the Faculty of Dentistry/Faculty of Pharmacy, Mahidol University Ethics Committee (no: MU-DT/PY-IRB 2020/017.1603, date: 16/03/2020).

Informed Consent: Informed consent was obtained from all participants.

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