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Procedural errors detected by cone beam tomography in cases with indication for retreatment: *in vivo* cross-sectional study

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ABSTRACT

Objectives: This study aimed to investigate the frequency and type of endodontic procedural errors in cases indicated for retreatment through cone-beam computed tomography (CBCT) analysis.
Materials and Methods: The sample consisted of 96 CBCT scans, encompassing 122 permanent teeth with fully formed roots. Errors included perforation, instrument fracture, canal transportation, missed canals, and inadequate apical limit of filling. Additionally, potential risk factors were analyzed and subjected to statistical modeling.
Results: The most frequent procedural error observed was the inadequate apical limit of filling, followed by canal transportation, perforation, missed canal, and instrument fracture. Statistically significant associations were identified between various procedural errors and specific factors. These include canal transportation and root canal wall, with the buccal wall being the most commonly affected; missed canal and tooth type, particularly the palatine and second mesiobuccal canal canals; inadequate apical limit of filling and root curvature, showing a higher deviation to the mesial direction in severely curved canals; inadequate apical limit of filling and the presence of calcifications, with underfilling being the most frequent; canal transportation and periapical lesion, notably with deviation to the buccal direction; and the direction of perforation and periapical lesion, most frequently occurring to buccal direction.
Conclusions: CBCT emerges as a valuable tool in identifying procedural errors and associated factors, crucial for their prevention and management.

Keywords: Cone beam computed tomography; Endodontics; Root canal therapy

INTRODUCTION

The primary goal of endodontic treatment is to reduce microbial load, aiming to eliminate the intracanal infection to levels compatible with the healing of the periapical tissues [1]. Nonetheless, 5%–20% of endodontic treatments result in post-treatment apical periodontitis, often attributed to anatomical variations that pose challenges and contribute

Author Contributions

Conceptualization: Valverde Haro HP, Rupaya CR; Data curation: Valverde Haro HP; Formal analysis: Valverde Haro HP; Funding acquisition: Valverde Haro HP; Investigation: Valverde Haro HP; Methodology: Rupaya CR; Project administration: Rupaya CR; Resources: Valverde Haro HP; Software: Valverde Haro HP; Supervision: Rupaya CR; Validation: Alves FRF; Visualization: Valverde Haro HP; Writing - original draft: Valverde Haro HP, Alves FRF; Writing - review & editing: Alves FRF.

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to procedural errors [2]. These errors include perforations, instrument fractures, canal transportation, missed canals, and inadequate filling [3,4]. Factors such as root canal calcifications and pulp stones, occurring in 5.1% and 8% of cases, are commonly associated with procedural errors in endodontic practice [5].

The most common treatment alternative for cases with persistent periapical lesions is endodontic retreatment, particularly recommended for inadequately treated cases [6]. However, retreatments are challenging in cases presenting procedural errors. Therefore, meticulous treatment planning, with attention to detail, is crucial to the successful resolution of these cases. In this regard, cone-beam computed tomography (CBCT) stands out as a valuable tool for identifying endodontic procedural errors. The 3-dimensional (3D) nature and high-quality imaging of CBCT offer optimal conditions for error analysis. Despite the availability of this advanced imaging technology, it is noteworthy that several CBCT studies have predominantly examined individual procedural errors, thereby limiting a comprehensive understanding of the various factors influencing treatment outcomes [7,8].

The present study aimed to investigate the frequency and type of endodontic procedural errors in cases indicated for retreatment through CBCT analysis. Additionally, potential risk factors were analyzed and subjected to statistical modeling.

MATERIALS AND METHODS

This cross-sectional descriptive study received approval from the Institutional Research Ethics Committee (approval No. 209552).

Sample selection and evaluation

A sample calculation estimated the number of CBCT scans required to test pairwise associations between variables. This calculation took into account findings from similar prior studies [9,10]. Given the variability in these findings, 3 sample calculations were performed, each based on different assumptions: a weak association (r = 0.3), a moderate association (r = 0.55), and a strong association (r = 0.8). With a 5% alpha error and a 20% beta error, the minimum number of scans needed was estimated to be 85.

The sample consisted of 96 CBCT scans, encompassing 122 permanent teeth with fully formed roots and radiographic evidence of previous endodontic treatment, with retreatment indication. CBCT's indications were based on the 7th and 8th recommendations of the AAE/AAOMR position statement [11]. The data collection occurred between January 1st, 2020 and June 30th, 2022. The scans were obtained using the GIANO HR CBCT equipment (NewTon, Imola, Italy), with FOV limited to 6 × 6 mm, a voxel from 68 to 300 μm, 16 mAs, 90 kVp, and a scan time in the Best Quality function of 16.8–3.6 seconds.

Two examiners underwent training and calibration under the guidance of an expert radiologist with over 10 years of experience in CBCT image measurement, interpretation, and diagnosis. This training was performed with a set of 20 CBCT scans and was focused on standardizing CBCT evaluation. CBCT evaluation was performed using Horos software version V3.3.6 (HOROS, Horos project, Annapolis, MD, USA). Scans were excluded if visualization difficulties due to artifacts were noted by at least 1 examiner. From an initial sample of 120 scans, 24 were excluded due to artifacts, resulting in the 96 that composed the

final sample. Substantial agreement between observers was achieved (Kappa value of 0.90). In cases where there was no consensus in the evaluation, a joint review was conducted until consensus was reached.

Evaluation of procedural errors

1. Perforation and direction

The prevalence and direction of perforations were analyzed across the 3 tomographic sections, with greater emphasis on the axial and sagittal sections. The aim was to identify whether perforation occurred and its location within the root canal—whether buccal, distal, mesial, or palatal (**Figure 1**).

2. Instrument fracture

The frequency of instrument fracture was assessed, and the location of the instrument fragment within the root canal was identified (apical, middle, or coronal third). Special attention was given to analyzing sagittal and axial slices of the CBCT (**Figure 2**).
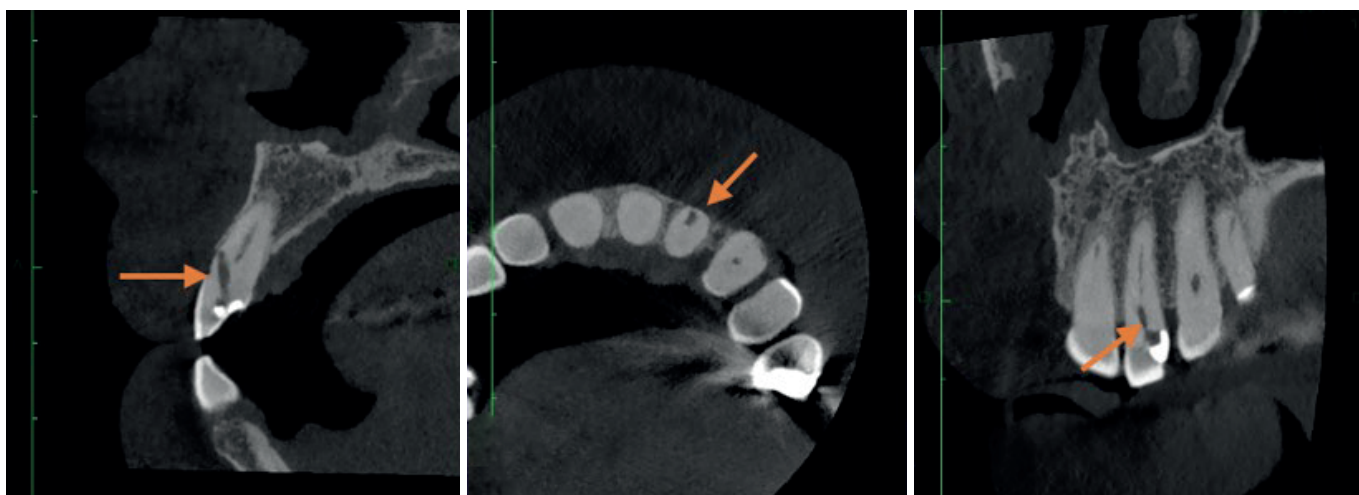

Figure 1. Dynamic cone-beam computed tomography analysis for identification of perforation in the right lateral incisor.

Figure 2. Dynamic cone-beam computed tomography analysis for identification of fractured instrument in lower left first molar.

3. Canal transportation
The filling material trajectory was compared with the canal direction, and any detected deviations were categorized as buccal, distal, mesial, or palatal. Evaluation involved analysis of sagittal, axial, and coronal sections of the CBCT (**Figure 3**).

4. Missed canal
Teeth images were analyzed for the occurrence of at least 1 untreated canal, defined as those without any evidence of filling material from the coronal orifice to the apex, and its association with the presence of apical periodontitis, primarily assessed on axial section images (**Figure 4**) [12].

5. Apical limit of filling
The extent of filling was evaluated using a nominal scale: underfilled (> 2 mm short from the
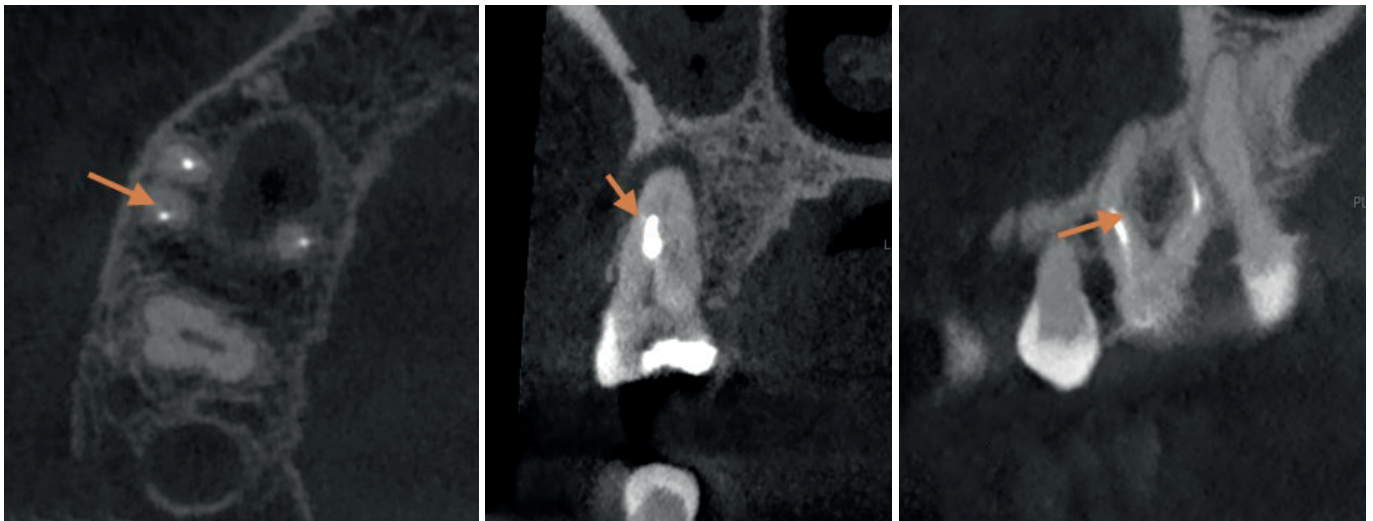

Figure 3. Dynamic cone-beam computed tomography analysis for identification of canal transportation in upper right first molar.
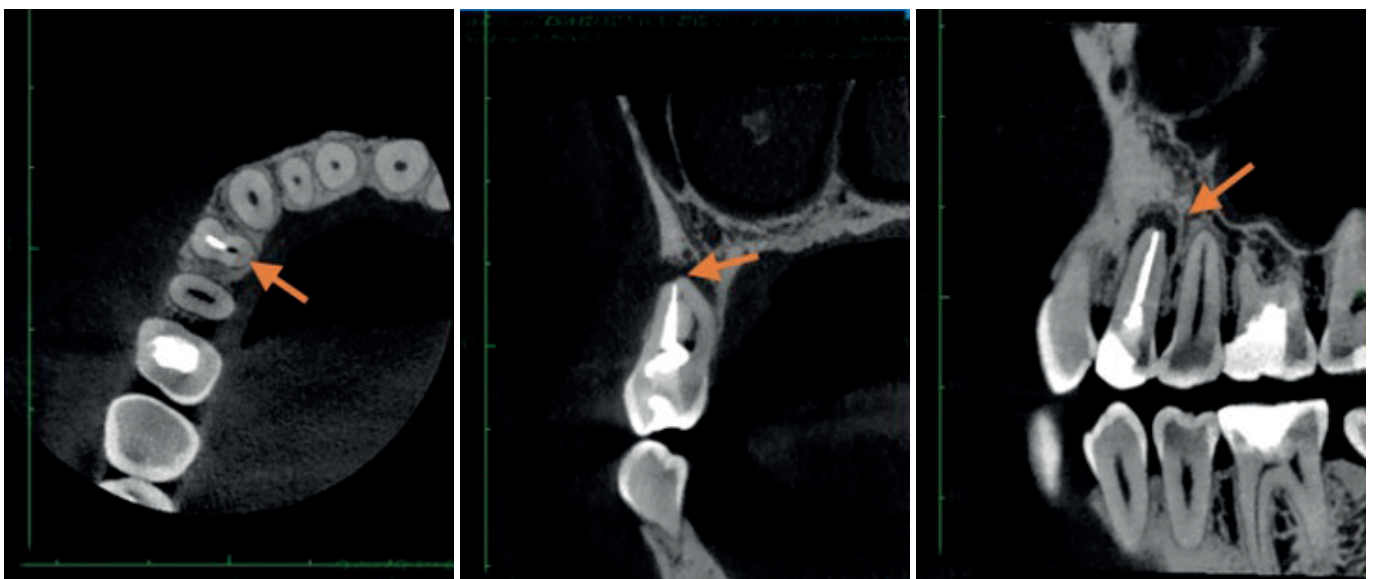
Figure 4. Dynamic analysis of cone-beam computed tomography for identification of missed canal.
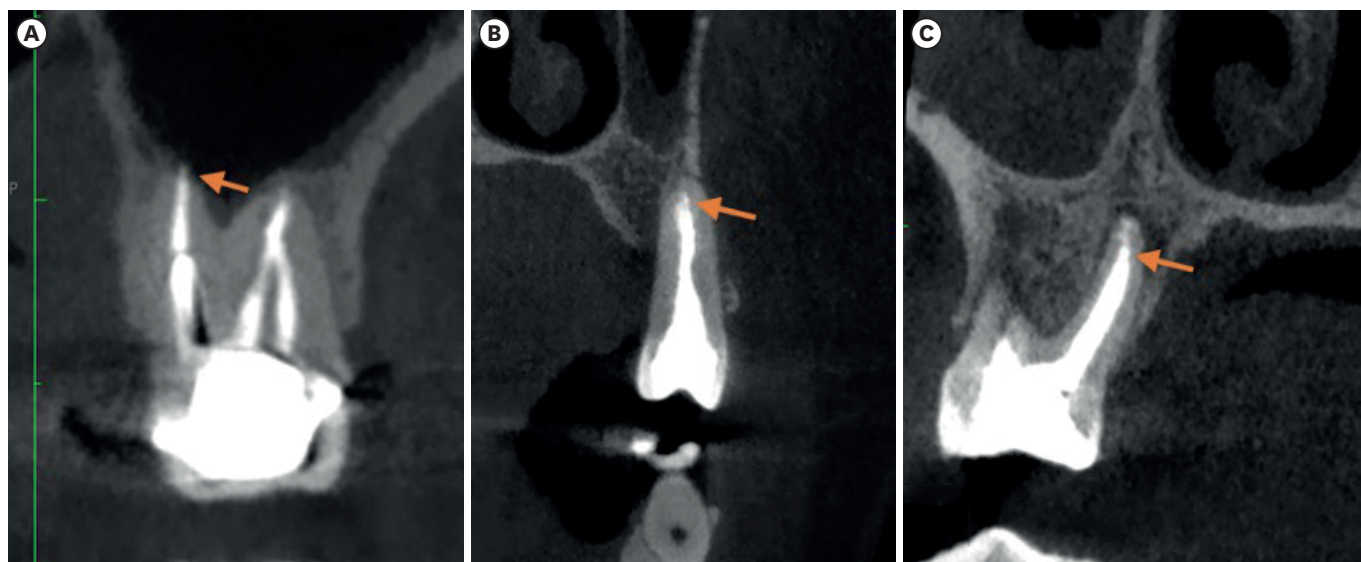
Figure 5. Identification of (A) molar with an overfilled canal, (B) premolar at the appropriate level and (C) palatal canal of an underfilled upper molar.

apex), overfilled, both understandable as inadequate, and adequate (0–2 mm short from the apex). Initial assessment was conducted on sagittal section images, with confirmation on axial slices (**Figure 5**).

6. Associated factors

Several associated factors were also evaluated: (a) presence of calcifications (**Figure 6**); (b) tooth type (anterior, premolars, and molars) (**Figure 7**); (c) periapical lesion, defined by disruption of lamina dura continuity and the presence of a radiolucent area around the root apex at least twice as thick as the normal periodontal ligament space (**Figure 8**); and (d) root curvature angle according to the Schneider's method, modified by the inclusion of one more category (mild curvature) (**Figure 9**) [13,14].
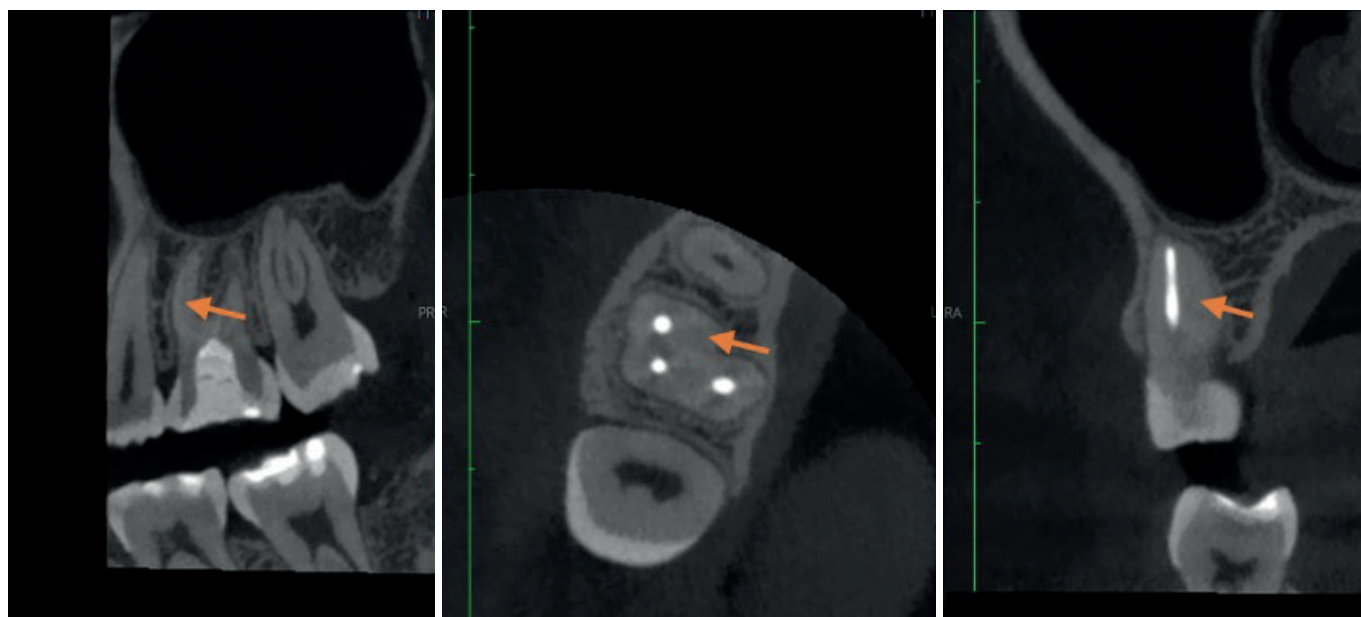
Figure 6. Identification of second mesiobuccal canal calcification in upper left first molar.
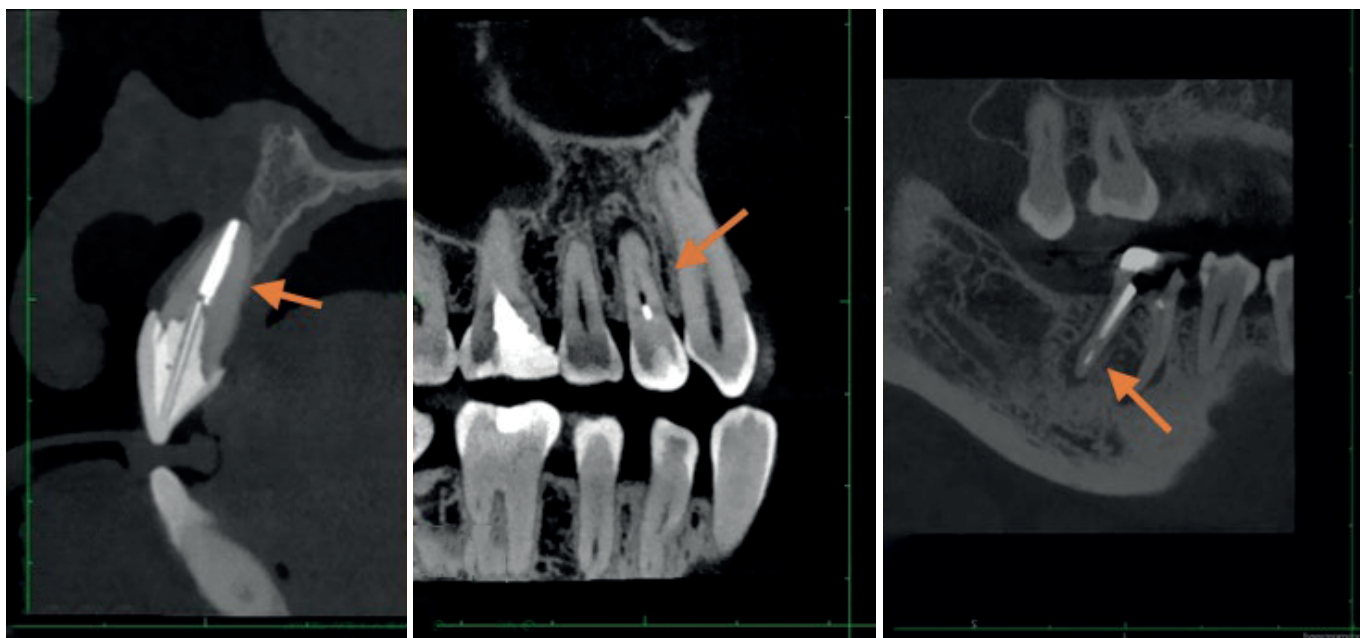
Figure 7. Identification of anterior, premolar and molar tooth type.
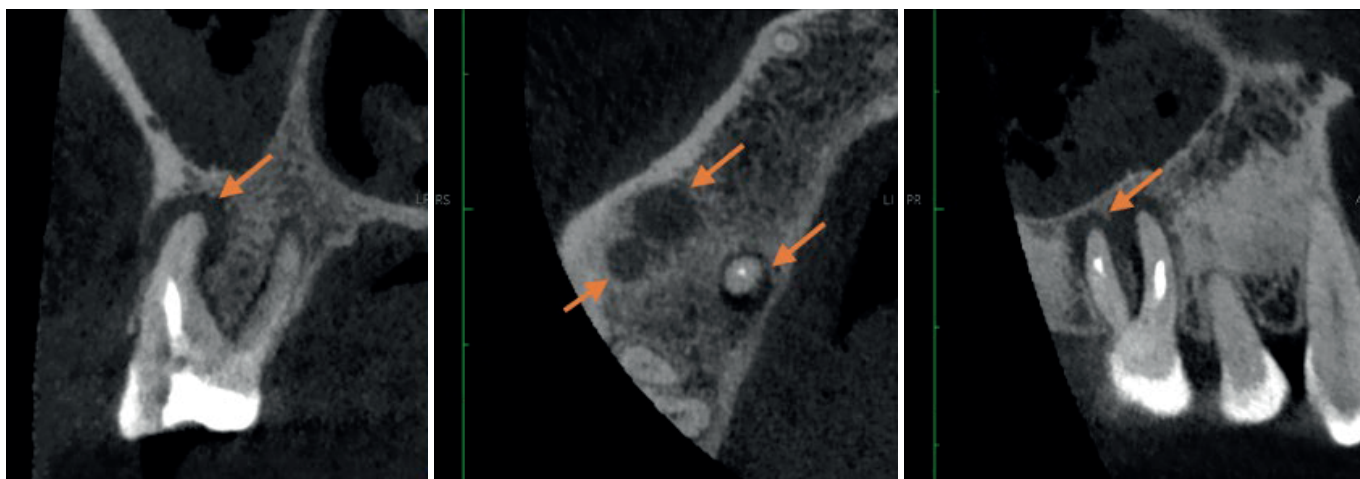
Figure 8. Identification of periapical lesion in upper right first molar.

Statistical analysis

The data were analyzed using Stata software v. 17 (StataCorp, College Station, TX, USA). Descriptive statistics were computed to understand the distribution of variables via univariate analysis. Absolute and relative frequencies were obtained and represented with tables. For inferential statistics, bivariate analysis was conducted between dichotomous qualitative variables utilizing χ^2 and Fisher's analysis. These tests determined the association between endodontic procedural errors and associated factors. Response categories with counts less than 5 were collapsed to ensure statistical robustness.
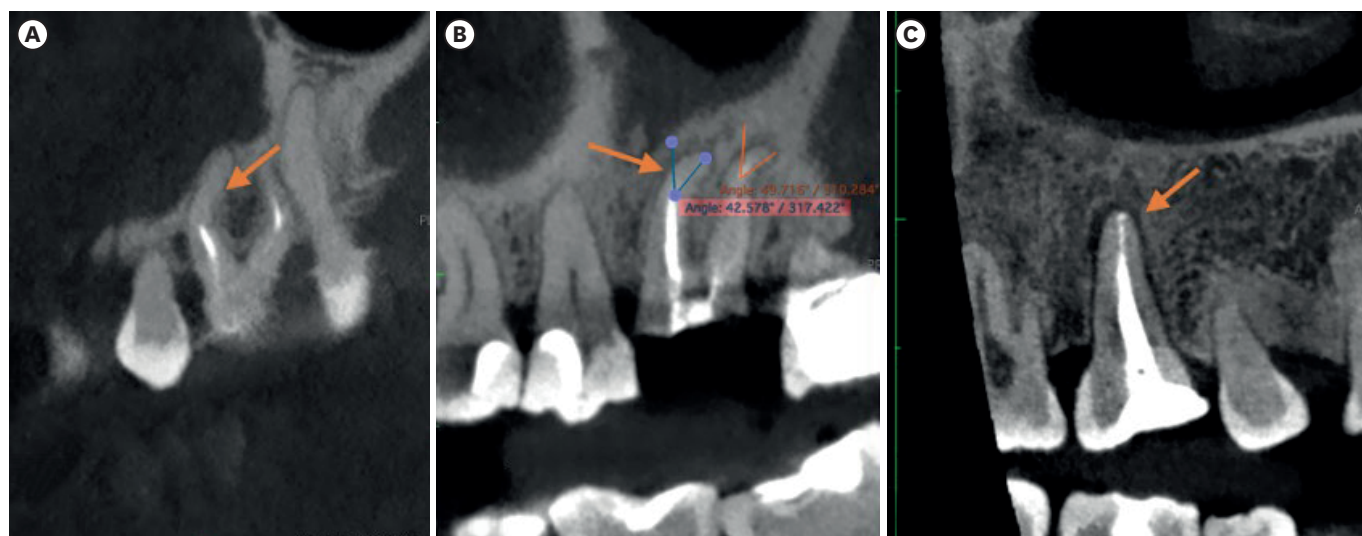
Figure 9. Identification of type of curvature, (A) moderate, (B) severe and (C) straight.

RESULTS

The most frequent procedural error observed was the inadequate apical limit of filling (82.38%, $n = 187$), followed by canal transportation (68.72%, $n = 156$), canal perforation (63.44%, $n = 144$), missed canal (16.30%, $n = 37$), and instrument fracture (1.76%, $n = 4$). For a detailed prevalence of each procedural error, please refer to **Table 1**.

Table 1. Type and frequency of endodontic procedural errors per canal ($n = 227$)

Procedural errors	Values
Perforation	
Without perforation	83 (36.56)
Buccal	54 (23.79)
Distal	27 (11.89)
Mesial	39 (17.18)
Palatal	24 (10.57)
Root canal transportation	
No transport	71 (31.28)
Buccal	64 (28.19)
Distal	24 (10.57)
Mesial	42 (18.50)
Palatal	26 (11.45)
Instrument fracture	
No fracture	223 (98.24)
Middle third	4 (1.76)
Missed canals	
No missed canal	190 (83.70)
Single canal	1 (0.44)
Mesiobuccal	6 (2.64)
Mesiolingual	2 (0.88)
MB2	9 (3.96)
Distobuccal	5 (2.20)
Palatal	10 (4.41)
Buccal	4 (1.76)
Root filling extension	
Underfilled	114 (50.22)
Overfilled	33 (14.54)
Adequate	40 (17.62)
Unfilled	40 (17.62)

Values are presented as number (%).

Statistically significant associations ($p < 0.01$) were identified between various procedural errors and specific factors. These include canal transportation and root canal wall, with the buccal wall being the most commonly affected; missed canal and tooth type, particularly the palatine and second mesiobuccal canal (MB2) canals; inadequate apical limit of filling and root curvature, showing a higher deviation to the mesial direction in severely curved canals; inadequate apical limit of filling and the presence of calcifications, with underfilling being the most frequent; canal transportation and periapical lesion, notably with deviation to the buccal direction in these cases; and the direction of perforation and periapical lesion, most frequently occurring to buccal direction. Conversely, no statistically significant association was found between endodontic procedure error and tooth quadrant ($p > 0.05$). Detailed frequencies are provided in the respective **Tables 2-6**.

DISCUSSION

In contemporary endodontics, the importance of CBCT to assess the quality of previous endodontic treatment is well recognized being probably the greater ally of the clinician to obtain accurate diagnosis and decision-making, especially in cases of posttreatment apical

Table 2. Procedural errors according to tooth type

Procedural errors	Tooth type							
	Upper Incisors	Upper canines	Upper premolars	Upper molars	Lower incisors	Lower premolars	Lower molars	Total
Perforation								
Without perforation	13 (5.73)	2 (0.88)	19 (8.37)	34 (14.98)	0 (0.00)	1 (0.44)	14 (6.17)	83 (36.56)
Buccal	15 (6.61)	3 (1.32)	11 (4.85)	15 (6.61)	0 (0.00)	2 (0.88)	8 (3.52)	54 (23.79)
Distal	2 (0.88)	1 (0.44)	3 (1.32)	13 (5.73)	1 (0.44)	0 (0.00)	7 (3.08)	27 (11.89)
Mesial	9 (3.96)	0 (0.00)	4 (1.76)	15 (6.61)	0 (0.00)	2 (0.88)	9 (3.96)	39 (17.18)
Palatal	3 (1.32)	0 (0.00)	2 (0.88)	10 (4.41)	0 (0.00)	2 (0.88)	7 (3.08)	24 (10.57)
Pearson χ^2 (1) = 0.6996 Pr = 0.403								
Root canal transportation								
No transport	6 (2.64)	0 (0.00)	16 (7.05)	33 (14.54)	0 (0.00)	1 (0.44)	15 (6.61)	71 (31.28)
Buccal	19 (8.37)	4 (1.76)	14 (6.17)	16 (7.05)	0 (0.00)	2 (0.88)	9 (3.96)	64 (28.19)
Distal	2 (0.88)	1 (0.44)	2 (0.88)	12 (5.29)	1 (0.44)	0 (0.00)	6 (2.64)	24 (10.57)
Mesial	11 (4.85)	1 (0.44)	4 (1.76)	15 (6.61)	0 (0.00)	3 (1.32)	8 (3.52)	42 (18.50)
Palatal	4 (1.76)	0 (0.00)	3 (1.32)	11 (4.85)	0 (0.00)	1 (0.44)	7 (3.08)	26 (11.45)
Pearson χ^2 (1) = 6.9223 Pr = 0.009								
Instrument fracture								
Unfractured	42 (18.50)	6 (2.64)	39 (17.18)	85 (37.44)	1 (0.44)	7 (3.08)	43 (18.94)	223 (98.24)
Middle third	0 (0.00)	0 (0.00)	0 (0.00)	2 (0.88)	0 (0.00)	0 (0.00)	2 (0.88)	4 (1.76)
Fisher's exact = 1.000/1-sided Fisher's exact = 0.438								
Missed canals								
Single canal	1 (0.44)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	1 (0.44)
Mesiobuccal	0 (0.00)	0 (0.00)	0 (0.00)	4 (1.76)	0 (0.00)	0 (0.00)	2 (0.88)	6 (2.64)
Mesiolingual	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	2 (0.88)	2 (0.88)
MB2	0 (0.00)	0 (0.00)	0 (0.00)	9 (3.96)	0 (0.00)	0 (0.00)	0 (0.00)	9 (3.96)
Distobuccal	0 (0.00)	0 (0.00)	0 (0.00)	4 (1.76)	0 (0.00)	0 (0.00)	1 (0.44)	5 (2.20)
Palatal	0 (0.00)	0 (0.00)	7 (3.08)	3 (1.32)	0 (0.00)	0 (0.00)	0 (0.00)	10 (4.41)
Buccal	0 (0.00)	0 (0.00)	2 (0.88)	2 (0.88)	0 (0.00)	0 (0.00)	0 (0.00)	4 (1.76)
Pearson χ^2 (1) = 7.3180 Pr = 0.007								
Root filling extension								
Underfilled	19 (8.37)	4 (1.76)	15 (6.61)	47 (20.70)	1 (0.44)	2 (0.88)	26 (11.45)	114 (50.22)
Overfilled	13 (5.73)	0 (0.00)	6 (2.64)	11 (4.85)	0 (0.00)	3 (1.32)	0 (0.00)	33 (14.54)
Adequate	9 (3.96)	2 (0.88)	10 (4.41)	8 (3.52)	0 (0.00)	2 (0.88)	9 (3.96)	40 (17.62)
Unfilled	1 (0.44)	0 (0.00)	8 (3.52)	21 (9.25)	0 (0.00)	0 (0.00)	10 (4.41)	40 (17.62)
Pearson χ^2 (1) = 0.5117 Pr = 0.474								

Values are presented as number (%).

Table 3. Procedural errors according to the type of root curvature

Procedural errors	Type of root curvature				
	Straight (≤ 5°)	Mild (5°–10°)	Moderate (10°–20°)	Severe (25°–70°)	Total
Perforation					
Without perforation	60 (26.43)	7 (3.08)	5 (2.20)	11 (4.85)	83 (36.56)
Buccal	38 (16.74)	8 (3.52)	1 (0.44)	7 (3.08)	54 (23.79)
Distal	13 (5.73)	4 (1.76)	2 (0.88)	8 (3.52)	27 (11.89)
Mesial	19 (8.37)	10 (4.41)	1 (0.44)	9 (3.96)	39 (17.18)
Palatal	18 (7.93)	3 (1.32)	2 (0.88)	1 (0.44)	24 (10.57)
Pearson χ^2 (8) = 15.3963 Pr = 0.052					
Root canal transportation					
No transport	46 (20.26)	9 (3.96)	5 (2.20)	11 (4.85)	71 (31.28)
Buccal	49 (21.59)	7 (3.08)	1 (0.44)	7 (3.08)	64 (28.19)
Distal	11 (4.85)	4 (1.76)	2 (0.88)	7 (3.08)	24 (10.57)
Mesial	22 (9.69)	9 (3.96)	1 (0.44)	10 (4.41)	42 (18.50)
Palatal	20 (8.81)	3 (1.32)	2 (0.88)	1 (0.44)	26 (11.45)
Pearson χ^2 (8) = 13.7770 Pr = 0.088					
Instrument fracture					
Unfractured	146 (64.32)	31 (13.66)	11 (4.85)	35 (15.42)	223 (98.24)
Middle third	2 (0.88)	1 (0.44)	0 (0.00)	1 (0.44)	4 (1.76)
Fisher's exact = 0.612/1-sided Fisher's exact = 0.434					
Missed canals					
No missed canal	131 (57.71)	25 (11.01)	7 (3.08)	27 (11.89)	190 (83.70)
Single canal	1 (0.44)	0 (0.00)	0 (0.00)	0 (0.00)	1 (0.44)
Mesiobuccal	1 (0.44)	3 (1.32)	0 (0.00)	2 (0.88)	6 (2.64)
Mesiolingual	1 (0.44)	1 (0.44)	0 (0.00)	0 (0.00)	2 (0.88)
MB2	1 (0.44)	2 (0.88)	0 (0.00)	6 (2.64)	9 (3.96)
Distobuccal	5 (2.20)	0 (0.00)	0 (0.00)	0 (0.00)	5 (2.20)
Palatal	6 (2.64)	1 (0.44)	2 (0.88)	1 (0.44)	10 (4.41)
Buccal	2 (0.88)	0 (0.00)	2 (0.88)	0 (0.00)	4 (1.76)
Pearson χ^2 (1) = 7.2211 Pr = 0.007					
Root filling estension					
Underfilled	67 (29.52)	18 (7.93)	5 (2.20)	24 (10.57)	114 (50.22)
Overfilled	24 (10.57)	6 (2.64)	1 (0.44)	2 (0.88)	33 (14.54)
Adequate	37 (16.30)	2 (0.88)	1 (0.44)	0 (0.00)	40 (17.62)
Unfilled	20 (8.81)	6 (2.64)	4 (1.76)	10 (4.41)	40 (17.62)
Pearson χ^2 (6) = 23.7269 Pr = 0.001					

Values are presented as number (%).

periodontitis [12,13]. Using CBCT, the present study significantly advances the understanding of conditions associated with failures in endodontic procedures. By incorporating factors such as root canal anatomy, tooth type, presence of periapical lesion, and root curvature angle, this research highlights aspects often overlooked in similar studies, offering a detailed perspective on how these factors collectively impact endodontic outcomes [7,8]. This approach contributes to a more comprehensive understanding of endodontic procedural failures.

In this investigation, underfilling emerged as the most prevalent endodontic procedural error, affecting 50.22% of the cases. This finding aligns with previous research, including a study by Nascimento *et al.* [15] which identified insufficient filling of root canals as the predominant procedural error (52.47%). Similarly, a previous study found underfilled canals to be the most prevalent error (85.9%), with a statistically significant association noted in teeth exhibiting straight curvature (22.6%)—specifically, Vertucci type I—and the presence of a periapical lesion (77.3%) [16]. Moreover, a cohort study evaluating 1259 endodontically treated teeth observed that insufficient obturation, extending beyond or shorter than 2 mm from the apex, significantly reduced the odds ratio for treatment success [17].

Table 4. Procedural errors according to the presence of calcifications

Procedural errors	Calcification		
	Yes	No	Total
Perforation direction			
Without perforation	8 (3.52)	75 (33.04)	83 (36.56)
Buccal	3 (1.32)	51 (22.47)	54 (23.79)
Distal	3 (1.32)	24 (10.57)	27 (11.89)
Mesial	2 (0.88)	37 (16.30)	39 (17.18)
Palatal	2 (0.88)	22 (9.69)	24 (10.57)
Pearson χ^2 (1) = 0.5235 Pr = 0.469			
Root canal transportation			
No transport	9 (3.96)	62 (27.31)	71 (31.28)
Buccal	3 (1.32)	61 (26.87)	64 (28.19)
Distal	1 (0.44)	23 (10.13)	24 (10.57)
Mesial	1 (0.44)	41 (18.06)	42 (18.50)
Palatal	4 (1.76)	22 (9.69)	26 (11.45)
Pearson χ^2 (1) = 3.1882 Pr = 0.074			
Instrument fracture			
Unfractured	18 (7.93)	205 (90.31)	223 (98.24)
Middle third	0 (0.00)	4 (1.76)	4 (1.76)
Fisher's exact = 1.000/1-sided Fisher's exact = 0.717			
Missed canals			
No missed canal	7 (3.08)	183 (80.62)	190 (83.70)
Single canal	1 (0.44)	0 (0.00)	1 (0.44)
Mesiobuccal	1 (0.44)	5 (2.20)	6 (2.64)
Mesiolingual	1 (0.44)	1 (0.44)	2 (0.88)
MB2	6 (2.64)	3 (1.32)	9 (3.96)
Distobuccal	0 (0.00)	5 (2.20)	5 (2.20)
Palatal	1 (0.44)	9 (3.96)	10 (4.41)
Buccal	1 (0.44)	3 (1.32)	4 (1.76)
Pearson χ^2 (1) = 28.7759 Pr = 0.000			
Root filling extension			
Underfilled	5 (2.20)	109 (48.02)	114 (50.22)
Overfilled	2 (0.88)	31 (13.66)	33 (14.54)
Adequate	1 (0.44)	39 (17.18)	40 (17.62)
Unfilled	10 (4.41)	30 (13.22)	40 (17.62)
Pearson χ^2 (3) = 19.6993 Pr = 0.000			

Values are presented as number (%).

Regarding associated factors, a higher prevalence of underfilled canals was observed in straight roots (29.52%), consistent with findings from a previous study, where underfilled canals were significantly more prevalent in teeth with straight canals (22.6%) [16]. Another factor associated with underfilled canals was the presence of periapical lesions, aligning with a previous study [18]. Inadequate filling allows bacteria and other microorganisms to invade the root canal or provide space for those that persist after treatment to proliferate, thereby maintaining or contributing to the development of post-treatment apical periodontitis [19]. The high prevalence of inadequate apical filling limits underscores several critical challenges in endodontic procedures. Technical difficulties in achieving an optimal apical seal. This issue is compounded by the clinician's skill and experience, as less experienced operators may struggle to prepare and thoroughly clean the apical region, jeopardizing the filling procedures.

Canal transportation, the second most prevalent error in our study (28.19%), demonstrated significant associations with the buccal wall of upper incisors, consistent with previous research [20]. The fact that the access cavities of upper incisors are angulated in the palatal direction, makes the buccal canal wall more susceptible to deviations and perforations. Studies have indicated that an apical transposition of more than 0.3 mm compromises the

Table 5. Endodontic procedure errors according to the presence of periapical reaction

Procedural errors	Periapical reaction		
	Presence	Absence	Total
Fenestration direction			
Without perforation	67 (29.52)	16 (7.05)	83 (36.56)
Buccal	40 (17.62)	14 (6.17)	54 (23.79)
Distal	26 (11.45)	1 (0.44)	27 (11.89)
Mesial	32 (14.10)	7 (3.08)	39 (17.18)
Palatal	11 (4.85)	13 (5.73)	24 (10.57)
Pearson χ^2 (4) = 20.6146 Pr = 0.000			
Root canal transportation			
No transport	56 (24.67)	15 (6.61)	71 (31.28)
Buccal	51 (22.47)	13 (5.73)	64 (28.19)
Distal	23 (10.13)	1 (0.44)	24 (10.57)
Mesial	34 (14.98)	8 (3.52)	42 (18.50)
Palatal	12 (5.29)	14 (6.17)	26 (11.45)
Pearson χ^2 (4) = 19.8368 Pr = 0.001			
Instrument fracture level			
No fracture	174 (76.65)	49 (21.59)	223 (98.24)
Middle third	2 (0.88)	2 (0.88)	4 (1.76)
Fisher's exact = 0.219/1-sided Fisher's exact = 0.219			
Omission of root canals			
No missed canal	144 (63.44)	46 (20.26)	190 (83.70)
Single canal	0 (0.00)	1 (0.44)	1 (0.44)
Mesiobuccal	6 (2.64)	0 (0.00)	6 (2.64)
Mesiolingual	2 (0.88)	0 (0.00)	2 (0.88)
MB2	9 (3.96)	0 (0.00)	9 (3.96)
Distobuccal	4 (1.76)	1 (0.44)	5 (2.20)
Palatal	8 (3.52)	2 (0.88)	10 (4.41)
Buccal	3 (1.32)	1 (0.44)	4 (1.76)
Pearson χ^2 (1) = 2.0343 Pr = 0.154			
Root filling quality			
Underfilled	89 (39.21)	25 (11.01)	114 (50.22)
Overfilled	25 (11.01)	8 (3.52)	33 (14.54)
Adequate level	27 (11.89)	13 (5.73)	40 (17.62)
Unfilled	35 (15.42)	5 (2.20)	40 (17.62)
Pearson χ^2 (3) = 4.6713 Pr = 0.198			

Values are presented as number (%).

success of canal treatment and increases the risk of canal perforation [21,22]. This should be considered a limitation of the present study since the degree of transportation was not evaluated, but only its presence or absence.

The prevalence of perforations was 23.79%, with significant associations observed between perforation direction towards the buccal wall and the presence of periapical lesions. Perforations become a contributing factor to the persistence or recurrence of infection. In addition, it may expose the tooth root to the oral cavity [23]. However, the present results should be analyzed carefully concerning the association of procedural errors with tooth type. For instance, incisors and canines are more susceptible to having more perforations to the buccal side, given the nature of the access cavity. Similarly, canal transportation tends to occur on the outside of the curvature. Therefore, some results depend on the nature of the tooth being analyzed.

Missed canals accounted for 16.29% of the cases, consistent with previous studies reporting percentages ranging from 12% to 23% [12,13]. The most frequent missed canals were the palatal and MB2 from the upper molars, aligning with existing literature demonstrating a high prevalence of missed MB2 canals in the upper first and second molars [12,13].

Table 6. Procedural errors according to dental quadrant

Procedural errors	Dental quadrant				
	Upper right	Upper left	Lower left	Lower right	Total
Fenestration direction					
Without perforation	35 (15.42)	33 (14.54)	6 (2.64)	9 (3.96)	83 (36.56)
Buccal	16 (7.05)	28 (12.33)	1 (0.44)	9 (3.96)	54 (23.79)
Distal	10 (4.41)	9 (3.96)	4 (1.76)	4 (1.76)	27 (11.89)
Mesial	11 (4.85)	17 (7.49)	7 (3.08)	4 (1.76)	39 (17.18)
Palatal	7 (3.08)	8 (3.52)	3 (1.32)	6 (2.64)	24 (10.57)
Pearson χ^2 (12) = 15.9915 Pr = 0.192					
Root canal transportation					
No transport	27 (11.89)	28 (12.33)	5 (2.20)	11 (4.85)	71 (31.28)
Buccal	20 (8.81)	33 (14.54)	2 (0.88)	9 (3.96)	64 (28.19)
Distal	10 (4.41)	7 (3.08)	4 (1.76)	3 (1.32)	24 (10.57)
Mesial	14 (6.17)	17 (7.49)	7 (3.08)	4 (1.76)	42 (18.50)
Palatal	8 (3.52)	10 (4.41)	3 (1.32)	5 (2.20)	26 (11.45)
Pearson χ^2 (12) = 11.7629 Pr = 0.465					
Instrument fracture					
Unfractured	78 (34.36)	94 (41.41)	21 (9.25)	30 (13.22)	223 (98.24)
Middle third	1 (0.44)	1 (0.44)	0 (0.00)	2 (0.88)	4 (1.76)
Fisher's exact = 1.000/1-sided Fisher's exact = 0.566					
Missed canals					
Single canal	61 (26.87)	81 (35.68)	19 (8.37)	29 (12.78)	190 (83.70)
Mesiobuccal	0 (0.00)	1 (0.44)	0 (0.00)	0 (0.00)	1 (0.44)
Mesiolingual	3 (1.32)	1 (0.44)	1 (0.44)	1 (0.44)	6 (2.64)
MB2	0 (0.00)	0 (0.00)	0 (0.00)	2 (0.88)	2 (0.88)
Distobuccal	5 (2.20)	4 (1.76)	0 (0.00)	0 (0.00)	9 (3.96)
Palatal	3 (1.32)	1 (0.44)	1 (0.44)	0 (0.00)	5 (2.20)
Buccal	6 (2.64)	4 (1.76)	0 (0.00)	0 (0.00)	10 (4.41)
Single canal	1 (0.44)	3 (1.32)	0 (0.00)	0 (0.00)	4 (1.76)
Fisher's exact = 0.266					
Root filling extension					
Underfilled	43 (18.94)	42 (18.50)	13 (5.73)	16 (7.05)	114 (50.22)
Overfilled	10 (4.41)	20 (8.81)	0 (0.00)	3 (1.32)	33 (14.54)
Adequate	10 (4.41)	19 (8.37)	6 (2.64)	5 (2.20)	40 (17.62)
Unfilled	16 (7.05)	14 (6.17)	2 (0.88)	8 (3.52)	40 (17.62)
Pearson χ^2 (9) = 13.5785 Pr = 0.138					

Values are presented as number (%).

Our study revealed a statistically significant association between missed MB2 canals and severely curved upper molar roots, consistent with previous research, which emphasized the importance of 3D examinations in identifying curved canals that may be missed otherwise [24]. Conversely, missed palatal canals in upper premolars were associated with straight canals, in line with previous findings indicating a similar association in maxillary second premolars [25]. Besides, associations between missed palatal canals and the presence of calcifications were evident in the present study, highlighting the impact of calcifications on procedural errors. Notably, CBCT is an indispensable diagnostic tool for surgical and non-surgical retreatment cases, although its superiority varies depending on the specific condition being diagnosed.

Instrument fracture, despite being the least frequent error (1.76%) in the present study, poses challenges in diagnosis via CBCT, with periapical radiographs remaining the preferred diagnostic modality [26]. However, there is a growing trend among clinicians to rely on CBCT for making decisions regarding the management of fractured instruments [27].

CONCLUSIONS

In conclusion, underfilled canal was the most frequent error, especially in straight canals, irrespective of calcifications. Notably, canal transportation in upper incisors correlated with the buccal wall and the presence of periapical lesions. Missed canals were predominantly associated with severely curved mesiopalatal canals, palatal canals, and the presence of calcifications. Perforations were also frequent, particularly in cases with periapical lesions. CBCT emerges as a valuable tool in identifying procedural errors and associated factors, crucial for their prevention and management.

REFERENCES

1. Toia CC, Khoury RD, Corazza BJM, Orozco EIF, Valera MC. Effectiveness of 1-visit and 2-visit endodontic retreatment of teeth with persistent/secondary endodontic infection: a randomized clinical trial with 18 months of follow-up. J Endod 2022;48:4-14. **PUBMED** | **CROSSREF**

2. Gaêta-Araujo H, Fontenele RC, Nascimento EHL, Nascimento MDCC, Freitas DQ, de Oliveira-Santos C. Association between the root canal configuration, endodontic treatment technical errors, and periapical hypodensities in molar teeth: a cone-beam computed tomographic study. J Endod 2019;45:1465-1471. **PUBMED** | **CROSSREF**

3. Alamoudi RA, Alharbi AH, Farie GA, Fahim O. The value of assessing case difficulty and its effect on endodontic iatrogenic errors: a retrospective cross-sectional study. Libyan J Med 2020;15:1688916. **PUBMED** | **CROSSREF**

4. Yagmoor M, Bakhsh A, Mandourah O, Alsofi L. Management of a radiopaque foreign body associated with a lower first premolar: a case report. Clin Case Rep 2022;10:e05465. **PUBMED** | **CROSSREF**

5. da Cunha LZV, Solda C, Padoin K, Rigo L. Endodontic procedural errors: analysis of images from cone beam computed tomography. Forensic Imaging 2022;28:200493. **CROSSREF**

6. Siqueira JF Jr, Rôças IN. Clinical implications and microbiology of bacterial persistence after treatment procedures. J Endod 2008;34:1291-1301.e3. **PUBMED** | **CROSSREF**

7. Peña-Bengoa F, Cáceres C, Niklander SE, Meléndez P. Association between second mesiobuccal missed canals and apical periodontitis in maxillary molars of a Chilean subpopulation. J Clin Exp Dent 2023;15:e173-e176. **PUBMED** | **CROSSREF**

8. Ballikaya E, Koc N, Avcu N, Cehreli ZC. The quality of root canal treatment and periapical status of permanent teeth in Turkish children and teens: a retrospective CBCT study. Oral Radiol 2022;38:405-415. **PUBMED** | **CROSSREF**

9. Nouroloyouni A, Salem Milani A, Etminan A, Noorolouny S, Tavakkol E, Mikaieli Xiavi H, et al. Cone-beam computed tomography assessment of quality of endodontic treatment and prevalence of procedural errors in mandibular molars. Int J Clin Pract 2023;2023:3558974. **PUBMED** | **CROSSREF**

10. Alghamdi NS, Algarni YA, Ain TS, Alfaifi HM, AlQarni AA, Mashyakhi JQ, et al. Endodontic mishaps during root canal treatment performed by undergraduate dental students: an observational study. Medicine (Baltimore) 2021;100:e27757. **PUBMED** | **CROSSREF**

11. Fayad MI, Nair M, Levin MD, Benavides E, Rubinstein RA, Barghan S, et al. AAE and AAOMR joint position statement: use of cone beam computed tomography in endodontics 2015 update. Oral Surg Oral Med Oral Pathol Oral Radiol 2015;120:508-512. **PUBMED** | **CROSSREF**

12. Costa FF, Pacheco-Yanes J, Siqueira JF Jr, Oliveira ACS, Gazzaneo I, Amorim CA, et al. Association between missed canals and apical periodontitis. Int Endod J 2019;52:400-406. **PUBMED** | **CROSSREF**

13. Karabucak B, Bunes A, Chehoud C, Kohli MR, Setzer F. Prevalence of apical periodontitis in endodontically treated premolars and molars with untreated canal: a cone-beam computed tomography study. J Endod 2016;42:538-541. **PUBMED** | **CROSSREF**

14. Schneider SW. A comparison of canal preparations in straight and curved root canals. Oral Surg Oral Med Oral Pathol 1971;32:271-275. **PUBMED** | **CROSSREF**

15. Nascimento EHL, Gaêta-Araujo H, Andrade MFS, Freitas DQ. Prevalence of technical errors and periapical lesions in a sample of endodontically treated teeth: a CBCT analysis. Clin Oral Investig 2018;22:2495-2503. **PUBMED** | **CROSSREF**

16. Al Yahya RS, Al Attas MH, Javed MQ, Khan KI, Atique S, Abulhamael AM, *et al.* Root canal configuration and its relationship with endodontic technical errors and periapical status in premolar teeth of a Saudi sub-population: a cross-sectional observational CBCT study. Int J Environ Res Public Health 2023;20:1142. **PUBMED** | **CROSSREF**

17. Jurič R, Vidmar G, Blagus R, Jan J. Factors associated with the outcome of root canal treatment-a cohort study conducted in a private practice. Int Endod J 2024;57:377-393. **PUBMED** | **CROSSREF**

18. Villa-Machado PA, Restrepo-Patiño DM, Calvo-Trejos JP, Restrepo-Restrepo FA, Tobón-Arroyave SI, Provenzano JC, *et al.* Cone-beam computed tomographic and micro-computed tomographic evaluations of the root apexes of teeth with posttreatment apical periodontitis. J Endod 2020;46:1695-1701. **PUBMED** | **CROSSREF**

19. Siqueira JF Jr, Rôças IN. Present status and future directions: microbiology of endodontic infections. Int Endod J 2022;55(Supplement 3):512-530. **PUBMED** | **CROSSREF**

20. Pinto JC, de Faria-Vasconcelos K, Leite AF, Pedano MS, Guerreiro-Tanomaru J, Jacobs R, *et al.* Effect of foraminal enlargement on microcrack formation and apical transportation: a nano-CT assessment. Sci Rep 2023;13:4881. **PUBMED** | **CROSSREF**

21. Wu MK, Fan B, Wesselink PR. Leakage along apical root fillings in curved root canals. Part I: effects of apical transportation on seal of root fillings. J Endod 2000;26:210-216. **PUBMED** | **CROSSREF**

22. Hasheminia SM, Farhad A, Sheikhi M, Soltani P, Hendi SS, Ahmadi M. Cone-beam computed tomographic analysis of canal transportation and centering ability of single-file systems. J Endod 2018;44:1788-1791. **PUBMED** | **CROSSREF**

23. Wong J, Lee A, Zhang C. Diagnosis and management of apical fenestrations associated with endodontic diseases: a literature review. Eur Endod J 2021;6:25-33. **PUBMED**

24. Wu L, Ha WN, Decurcio DA, Estrela C, Rossi-Fedele G. Comparison of curvature severity between sagittal and coronal planes of mesiobuccal canals in permanent maxillary first molars using multiple complexity-risk criteria: a CBCT cross-sectional study of a Brazilian subpopulation. J Endod 2023;49:1682-1689.e4. **CROSSREF**

25. Wang FM, Rudman J, Walsh RM, Jalali P. A retrospective study of initial root canal treatment failure in maxillary premolars via using cone-beam computed tomography. J Am Dent Assoc 2023;154:471-478. **PUBMED** | **CROSSREF**

26. Ayatollahi F, Tabrizizadeh M, Razavi H, Mowji M. Diagnostic value of cone-beam computed tomography and digital periapical radiography in detection of separated instruments. Iran Endod J 2019;14:14-17. **PUBMED**

27. Özer SY, Özkan G, Çetin E, Özkan HD. A comparative study of cone-beam computed tomography and periapical radiographs in decision-making after endodontic instrument fractures. Int J Artif Organs 2017;40:510-514. **PUBMED** | **CROSSREF**