Four-year Outcome of Nonsurgical Root Canal Retreatment Using Cone-beam Computed Tomography: A Prospective Cohort Study

Ming-Ming Zhang, DDS,[*]
Gao-Feng Fang, MD,[*]
Xiao-Tong Chen, MD,[*] *and*
Yu-Hong Liang, DDS, PhD[*†]

SIGNIFICANCE

This prospective study provided information about the 4-year outcome and prognostic factors of nonsurgical root canal retreatment using contemporary techniques by measuring the volumetric change of periapical radiolucencies on CBCT scans.

ABSTRACT

Introduction: The purpose of this prospective study was to investigate the 4-year outcome and prognostic factors of nonsurgical root canal retreatment determined by measuring the volumetric change of periapical radiolucencies on cone-beam computed tomographic (CBCT) scans. **Methods:** Ninety-seven endodontically treated teeth from 80 patients diagnosed as apical periodontitis and indicated for root canal retreatment were included. Retreatment was performed by 7 endodontic specialists using a standardized treatment protocol. The teeth were reexamined clinically and radiographically 48–67 months after retreatment. The volume of preoperative and postoperative periapical radiolucencies on CBCT images was independently measured by 2 examiners. Radiographic outcome is presented in 4 categories: absence, reduction, enlargement, or unchanged. Reduction or enlargement was determined when the volumetric change of radiolucency was 20% or more. Multivariate logistic regression was performed for predictor analysis. **Results:** Sixty-two teeth (63.9%) from 50 patients returned for follow-up. Fifty-eight teeth were included in the prognostic analysis, all of which were symptom free. The 4 remaining teeth that had been extracted because of fracture were excluded. The total volume of periapical radiolucencies at 4 years postoperatively decreased by 94.6% compared with that preoperatively ($P < .001$), with an average reduction of 83.4% (95% confidence interval, 69.2%–97.5%). The periapical radiolucencies were determined as absence in 44 teeth (75.9%), reduction in 10 teeth (17.2%), unchanged in 1 tooth (1.7%), and enlargement in 3 teeth (5.2%). Tooth type was identified as an outcome predictor ($P < .05$). **Conclusions:** The 4-year outcome of endodontic retreatment is predictable, with a significant volumetric reduction in periapical radiolucencies. *(J Endod 2021;47:382–390.)*

KEY WORDS

Cone-beam computed tomography; nonsurgical root canal retreatment; periapical lesions; volumetric measurements

From the *Department of Cariology and Endodontology, Peking University School and Hospital of Stomatology and National Clinical Research Center for Oral Diseases and National Engineering Laboratory for Digital and Material Technology of Stomatology and Beijing Key Laboratory of Digital Stomatology, Beijing, China; and †Department of Stomatology, Peking University International Hospital, Beijing, China

Address requests for reprints to Dr Yu-Hong Liang, Department of Cariology and Endodontology, Peking University School and Hospital of Stomatology, Beijing, China 100081.
E-mail address: leungyuhong@sina.com
0099-2399/$ - see front matter

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The objective of root canal retreatment is to cure persistent or newly emerging periradicular disease after primary root canal treatment and/or to correct procedural errors, thus preserving the natural teeth healthy and functional[1]. Compared with primary treatment, retreatment represents a more complex and challenging treatment approach in the aspects of removing root filling material, regaining access to the canal systems with a potentially violated anatomy, and eliminating persistent and residual microbial floras[2].

With the use of new devices and materials such as operating microscopes, ultrasonic instruments, cone-beam computed tomography (CBCT) imaging, and bioceramics in practice, practitioners have more assistant power to address complex clinical situations in primary and secondary endodontic treatment. It is conceivable to expect a more predictable outcome. However, during the last 2 decades, there have been only 9 published prospective studies on nonsurgical retreatment, with the reported success rate ranging from 6%–93%[3–11].

CBCT imaging has already been widely used in the field of endodontic practice for the identification of root canal anatomy, the diagnosis of apical periodontitis, and the detection of root fracture and resorption[12]. It is also useful for aiding nonsurgical and surgical endodontic treatment planning[12]. In recent years, the increasing use of CBCT imaging has drawn attention to the use of this technology in outcome research of primary and secondary root canal treatment[10,13] and apical surgery[14]. Furthermore, by combining CBCT data with the volume rendering capability of software, the volume of a periapical lesion can be measured and compared preoperatively and postoperatively, providing a method to monitor the change of the periapical lesion quantitatively[10,14,15]. The aim of this prospective study was to evaluate the outcome and risk factors of nonsurgical root canal retreatment based on the 3-dimensional volumetric measurement of apical radiolucencies.

MATERIALS AND METHODS

Patient Inclusion

This prospective cohort study protocol was approved by the ethics board of Peking University Hospital of Stomatology, Beijing, China (nos. PKUSSIRB-2013057 and PKUSSIRB-201838108).

Patients with endodontically treated teeth that needed further intervention were selected according to the following criteria from June 2013 to October 2014 at the Department of Cariology and Endodontics of the Peking University School of Stomatology. All included teeth were radiographically examined by CBCT imaging preoperatively, diagnosed as apical periodontitis, and indicated for nonsurgical root canal retreatment. Pregnant women, patients with poorly controlled systemic diseases, and teeth with fractures were excluded. In total, 97 teeth from 80 patients were included in this study. Informed consent was obtained from each participant before the retreatment.

Treatment Protocol

Nonsurgical root canal retreatment was performed according to a predetermined treatment protocol by 7 endodontic specialists with at least 5 years of practice experience. After rubber dam isolation, all retreatment procedures were performed under operating microscopes (OPMI PICO; Carl Zeiss, Göttingen, Germany). Previous root filling materials were removed using hand and rotary instruments aided by heat, solvents, and ultrasonic instruments. The working length was determined with an apex locator (Raypex 6; VDW, Munich, Germany). Mechanical preparation was performed using a crown-down approach with nickel-titanium rotary instruments ProTaper Universal (Dentsply Maillefer, Ballaigues, Switzerland) or Reciproc (VDW). The final apical file was at least #25/.08 (ProTaper Universal F2 or Reciproc #25) according to the root canal anatomy. Each root canal was irrigated with 2 mL 5.25% sodium hypochlorite between each instrument. After completion of the instrumentation, root canals were dressed with calcium hydroxide paste (Multi-Cal; Pulpdent Corporation, Watertown, MA) for 1–2 weeks. At the second visit, final irrigation was accomplished with 5.25% sodium hypochlorite, 17% EDTA, and 2% chlorhexidine in sequence activated by an ultrasonic device with distilled water for 20 seconds. Canals were dried with paper points and obturated with gutta-percha (Dentsply Maillefer) and AH Plus sealer (Dentsply De Trey, Konstanz, Germany) using the warm vertical compaction technique (BeeFill 2in1, VDW). Glass ionomer cement was used as temporary restoration to seal the cavity (Fuji; GC America Inc, St Alsip, IL), and permanent restoration with composite resin or core buildup (3M Filtek P60; 3M ESPE, St Paul, MN) was completed within 2 weeks after retreatment.

Review

The patients were contacted 4 years after retreatment through telephone, e-mails, or letters. Efforts were made to encourage patients to attend the follow-up visit and to contact relocated patients. Clinical and radiographic examinations were performed for patients who attended the review at the hospital. For patients who could not be present at the hospital, a telephone recall was conducted, and the function and symptoms of the treated teeth were inquired and recorded. For patients whose teeth had been extracted, the time and cause of extraction were recorded.

The clinical examination included assessments of subjective discomfort, swelling, sinus tract formation, tenderness to palpation or percussion, mobility, periodontal pocket depth, and the quality of coronal restoration.

CBCT scans (preoperative and at recall) were acquired with the NewTom VGi (NewTom, Verona, Italy) using a small field of view (6×6 and 8×8 cm) with operating parameters of 110 kVp, automatic milliamperes, and an exposure time of 5.5 seconds. The CBCT images were reconstructed with NNT software, version 4.00.1 (NNT, Verona, Italy).

Two endodontists were trained and evaluated the CBCT images independently. A periapical lesion was determined when disruption of the lamina dura was detected, and the radiolucency associated with the radiographic apex was at least twice the width of the periodontal ligament space on at least 2 planes of the CBCT images. In case of disagreement, the case was discussed until a consensus was achieved. Then, the volume of the radiolucencies on the CBCT scans was measured by 2 examiners independently in Digital Imaging and Communication in Medicine format with Amira software (version 5.4.3; Visage Imaging GmbH, Berlin, Germany). A local threshold-determining algorithm was used with manual tracing intervention to determine the border of the lesion. The measurement was performed twice with a 1-month interval, and the first average measurement was used. The volume of radiolucencies on CBCT images before treatment and at recall was compared, and the percentage of change was calculated. The radiographic outcome is presented in 4 categories: absence, reduction, enlargement, or unchanged. Reduction or enlargement was defined as when the volumetric change of radiolucency was 20% or more[15].

Clinical Factors Assessed

Preoperative Factors

The following potential preoperative risk factors were evaluated: tooth type (anterior, premolar, or molar), sex (male or female), and age ($\leq$45 years or $>$45 years).

Preoperative Lesion Volume. In several but not all previous outcome studies, lesions $>$5 mm were associated with a reduced success rate[16]. The calculated volume of a spherical lesion with a diameter of 5 mm is 65 mm^3. In this study, the volume of preoperative lesion was classified into 2 categories: $\leq$65 mm^3 and $>$65 mm^3.

Complications of Primary Treatment. The missed canals, transportation, perforations, and instrument separation identified by the preoperative CBCT scans were included in the complications of primary treatment.

Intraoperative Factors

Root Filling Length. A flush filling was diagnosed on CBCT scans when the root filling was within 0–2 mm short of the apex in all coronal and sagittal sections. If the root filling was more than 2 mm short of the apex in all sections, a short filling was diagnosed. When the root filling extended beyond the apical end of the canal in any section, a long filling was diagnosed.

Root Filling Density. The density of the root filling in each root was evaluated on the basis of both the buccolingual and mesiodistal CBCT images by using a modified scoring system originally suggested by Kersten et al[17]. Satisfactory root filling density was defined as without voids or a longest void of less than 1 mm. Unsatisfactory root filling density was defined as with voids 1 mm in length or longer. The radiolucent line between the root filling and the canal wall extending all the way apically was referred to as a "mach band" and not scored as a void[18].

Postoperative Factors

Coronal Restoration. The quality of coronal restoration was assessed with a clinical examination. Satisfactory restoration was defined as no evidence of discrepancy, discoloration, or recurrent caries at the restoration margin and no history of decementation[19].

Statistical Analysis

The Cohen kappa and intraclass correlation coefficient (ICC) were used to assess interexaminer and intraexaminer agreement. A Wilcoxon signed rank test was used to compare the lesion volume before and after retreatment. For statistical analysis of the prognostic factors, the dependent variable was the dichotomous radiographic outcome (absence and presence of periapical radiolucencies). Bivariate associations between the treatment outcome and all the variables were examined using the chi-square test or the Fisher exact test. Multivariate logistic regression analysis was performed to identify prognostic factors and evaluate the risk of factors on outcomes. The level of significance was set at $\alpha = 0.05$.

RESULTS

Of the 97 teeth from 80 patients, 62 teeth from 50 patients were reviewed 48–67 months (mean = 53 months) after treatment. The recall rate was 64% (62/97) for teeth and 63% (50/80) for patients. Four teeth had been extracted because of tooth fracture, and the remaining 58 teeth from 46 patients were examined clinically and radiographically (29 women and 17 men, 22–58 years old). Thirty patients with 35 teeth were defined as "dropouts"; 18 patients with 22 teeth had relocated and could not be contacted, and the other 12 patients with 13 teeth declined presence at the hospital because of travel expenses or time schedule. For the latter group of patients, a telephone recall was conducted, and all of these teeth were functioning normally and free of symptoms. Response bias analysis with respect to preoperative factors (sex, age, preoperative lesion volume, and tooth type) revealed no significant difference between the reviewed cases and the dropout cases (Table 1).

TABLE 1 - Analysis of Preoperative Clinical Factors in the Reviewed ($n = 62$) and Dropout Cases ($n = 35$)

Clinical factors	No. of teeth	Reviewed cases (%)	Dropout cases (%)	*P* value
Sex				.165
Male	29	22 (35.5)	7 (20.0)	
Female	68	40 (64.5)	28 (80.0)	
Age				.307
≤45 years	86	57 (91.9)	29 (82.9)	
>45 years	11	5 (8.1)	6 (17.1)	
Tooth type				.518
Anterior	46	27 (43.6)	19 (54.3)	
Premolar	22	16 (25.8)	6 (17.1)	
Molar	29	19 (30.6)	10 (28.6)	
Preoperative lesion volume				.882
≤65 mm^3	74	47 (75.8)	27 (77.1)	
>65 mm^3	23	15 (24.2)	8 (22.9)	
Total	97	62	35	

The kappa scores for determining the presence or absence of periapical radiolucencies were 0.822 and 0.953 for the intraexaminer agreement and 0.864 for the interexaminer agreement. The ICC values of the CBCT volumetric measurements for the intraexaminer agreement were 0.989 and 0.994, respectively, and the ICC value for the interexaminer agreement was 0.956.

The volume and percentage change in the volume of periapical radiolucencies in 58 teeth based on preoperative and 4-year postoperative CBCT data are summarized in Table 2. All 58 recalled teeth were free of clinical signs or symptoms. The absence of radiolucencies was observed in 44 teeth (75.9%) (Fig. 1*A–H*). A reduction in radiolucencies was detected in 10 teeth (17.2%) (Fig. 2*A–H*). The volume of radiolucency was determined as unchanged in 1 tooth (1.7%) and enlargement in the remaining 3 teeth (5.2%) (Fig. 3*A–H*). The 4-year postoperative volume of periapical radiolucencies changed significantly compared with the preoperative volume ($P < .001$). The total volume of periapical radiolucencies decreased significantly by 94.6%, with an average volumetric reduction percentage of 83.4% (95% confidence interval, 69.2%–97.5%). The distribution of the percentage of volumetric reduction is shown in Figure 4.

The bivariate analysis for the effects of clinical factors on dichotomous outcome is summarized in Table 3. Logistic regression analysis revealed that tooth type significantly influenced the treatment outcome ($P < .05$), with odds ratio of 11.6 for premolars and 26.0 for molars.

DISCUSSION

Dealing with a previous failed endodontic situation is supposed to be 1 of the most challenging decisions in current endodontics[20]. Evidence-based outcome knowledge on different treatment alternatives should be available to dentists and patients when a specific treatment plan is made, such as retention of an endodontically involved tooth by endodontic retreatment versus extraction or replacement with a dental implant. The aim of this prospective cohort study was to evaluate the 4-year outcome of nonsurgical root canal retreatment and the potential prognostic factors to provide information about the benefit of contemporary materials and techniques.

All the teeth included in this study were retreated by endodontic specialists according to a predetermined treatment protocol, which included the application of a preoperative CBCT examination for planning and the use of the microsonic technique for improving visibility and accessibility. After a 4-year follow-up, 58 of the 97 teeth underwent clinical and radiographic examinations. By comparing the CBCT scans preoperatively and 4 years postoperatively, 75.9% of the teeth were determined as absence of radiolucency, which indicated the elimination of persistent infection in the root canal system and regaining of a healthy periapical condition in these teeth. This

TABLE 2 - The Volume and Percentage of Change for Periapical Lesions Based on Preoperative and 4-year Postoperative Cone-beam Computed Tomographic Data

No. of teeth	Preoperative lesion volume (mm^3)	Postoperative lesion volume (mm^3)	Percentage of lesion volume reduction (%)*	No.	Preoperative lesion volume (mm^3)	Postoperative lesion volume (mm^3)	Percentage of lesion volume reduction (%)*
1	451.5	0.0	100	30	12.4	0.0	100
2	376.3	0.0	100	31	12.2	0.0	100
3	339.0	24.9	93	32	11.4	3.7	68
4	166.5	11.3	93	33	10.0	0.0	100
5	162.1	11.7	93	34	9.6	0.0	100
6	161.7	0.0	100	35	8.0	0.0	100
7	156.1	0.0	100	36	7.3	0.0	100
8	135.8	0.0	100	37	5.7	6.8	−19
9	115.4	0.0	100	38	5.6	0.0	100
10	108.7	0.0	100	39	5.5	0.0	100
11	90.3	14.5	84	40	5.3	0.0	100
12	86.4	0.0	100	41	4.0	0.0	100
13	76.5	4.8	94	42	3.5	0.0	100
14	64.3	7.0	89	43	3.1	0.0	100
15	43.6	0.0	100	44	3.1	10.0	−218
16	39.3	30.0	24	45	2.6	0.0	100
17	36.9	0.0	100	46	2.6	0.0	100
18	30.7	0.0	100	47	2.5	0.0	100
19	27.7	0.0	100	48	2.1	0.0	100
20	24.6	0.0	100	49	1.8	0.0	100
21	24.3	3.4	86	50	1.7	0.0	100
22	20.8	0.0	100	51	1.6	0.0	100
23	20.6	30.6	−49	52	1.3	2.5	−90
24	20.3	0.0	100	53	1.0	0.0	100
25	15.9	0.0	100	54	0.8	0.0	100
26	13.5	0.0	100	55	0.8	0.0	100
27	13.2	0.0	100	56	0.8	0.0	100
28	12.9	0.0	100	57	0.8	0.0	100
29	12.8	1.5	88	58	0.7	0.0	100

*Percentage of lesion volume reduction (%) = (preoperative lesion volume − postoperative lesion volume)/preoperative lesion volume.

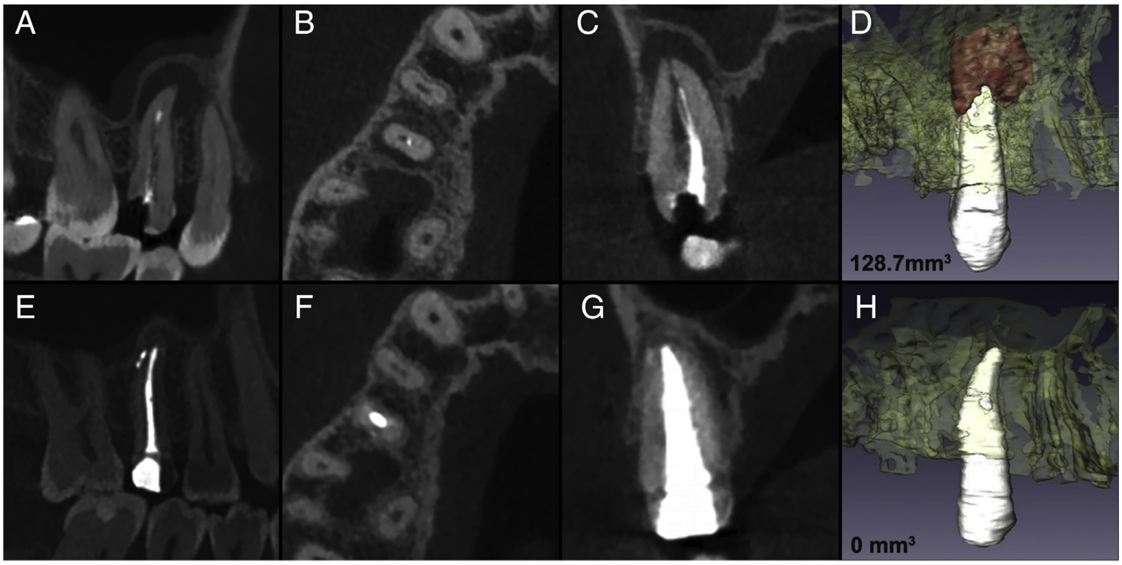

FIGURE 1 – Reconstructed images in multiplanes and 3 dimensions based on CBCT scans (*A–D*) preoperatively and (*E–H*) at the 4-year recall of tooth 15. (*D*) The preoperative periapical lesion with a volume of 128.7 mm^3 had completely resolved (*H*) at the 4-year follow-up.

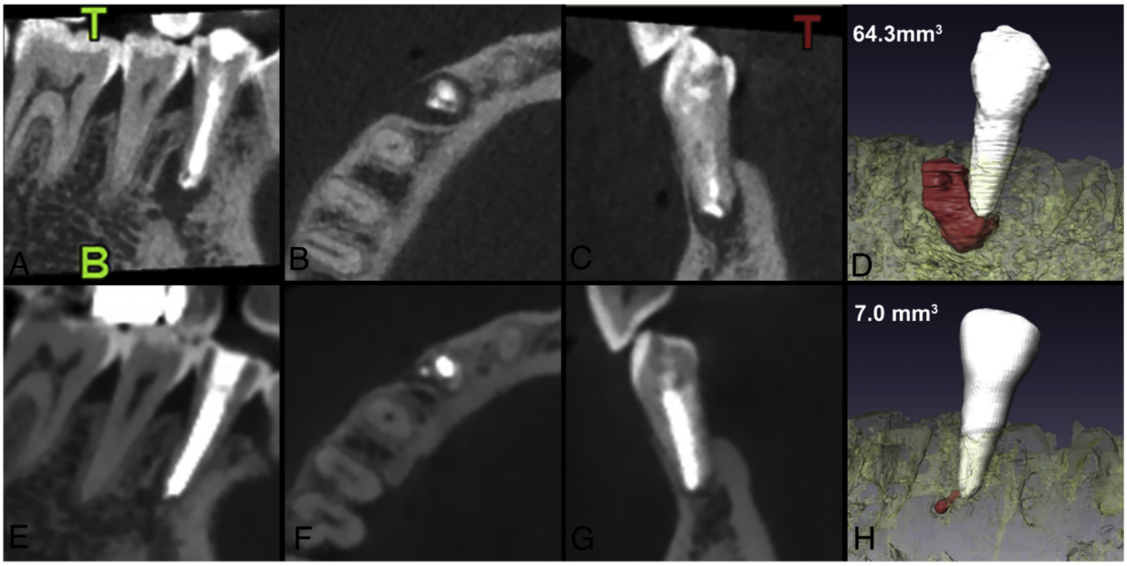

FIGURE 2 – (*A–D*) A 32-year-old woman with a large periapical lesion on a mandibular first premolar as shown on the preoperative multiplanar and 3-dimensional reconstructed CBCT images. (*A–C*) The tooth was detected with an open apex, thin root walls, and a poorly obturated root canal preoperatively. After removing the previous root filling materials, the root canal was cleaned with a size #80 final apical file. Then, mineral trioxide aggregate was placed and compacted for apexification. (*E–H*) The postoperative CBCT images revealed the volume of periapical lesions significantly reduced from (*D*) 64.3 mm^3 to (*H*) 7.0 mm^3 at 4 years after treatment.

finding seems comparable with the pooled weighted healed rate of 76.7% in a systematic review by Ng et al[16] from 17 outcome studies published up to the end of 2006 based on periapical radiographs. To date, there have been only 4 studies on endodontic retreatment outcomes based on CBCT data, and the reported rate of absence of radiolucency ranged from 6%–58%[3,4,10,14]. The results may vary because of differences in study design, such as sample characteristics, treatment protocol, follow-up time, and criteria for outcome assessment. In the study of Metska et al[10], 45 endodontically treated teeth with persistent apical periodontitis underwent root canal retreatment performed by postgraduate students, and 35 teeth (78%) were followed up 1 year after retreatment. According to a quantitative assessment of the 1-year volumetric changes in periapical lesions, 6% of the reviewed teeth were determined as absence of radiolucency. In 2 other prospective studies, by visual interpretation of the CBCT images 1 year after retreatment, the percentages of resolved lesions were 42% and 58%. In the retrospective study published by Curtis et al[14], the retreated teeth were

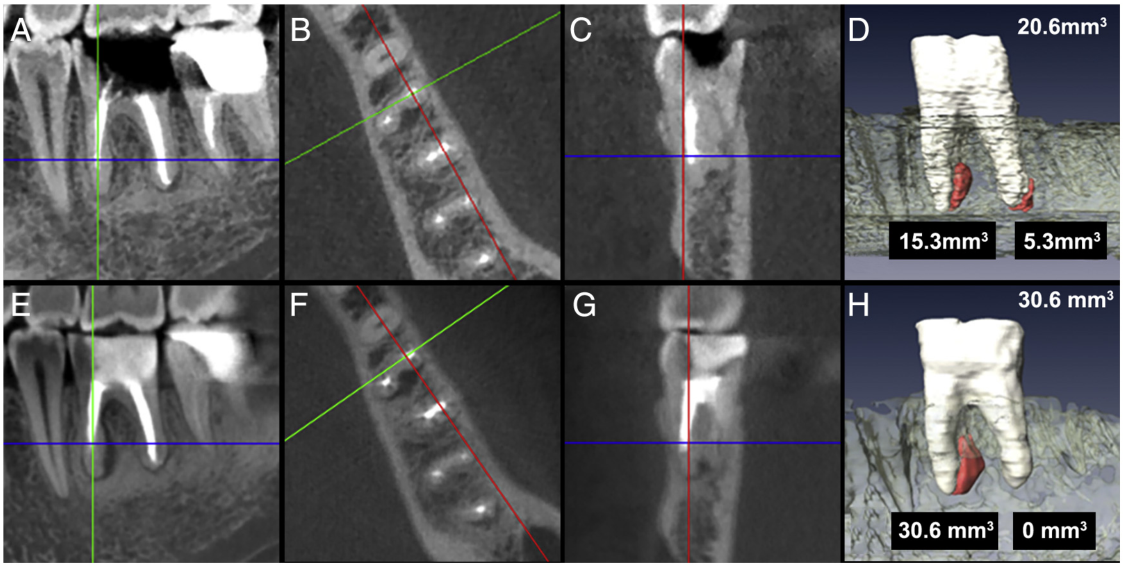

FIGURE 3 – The (*A–D*) preoperative and (*E–H*) 4-year postoperative CBCT images of tooth 36. With a previous canal transportation, the canal patency could not be achieved in the mesial root during retreatment. Although the periapical radiolucency around the distal root completely resolved, the radiolucency adhered to the mesial root enlarged. The volumetric measurement revealed an enlargement in the volume of radiolucency from (*D*) 20.6 mm^3 at the preoperative assessment to (*H*) 30.6 mm^3 at the 4-year follow-up evaluation. The retreatment outcome of the tooth was determined as a failure. A surgical intervention was considered and recommended in subsequent planning.

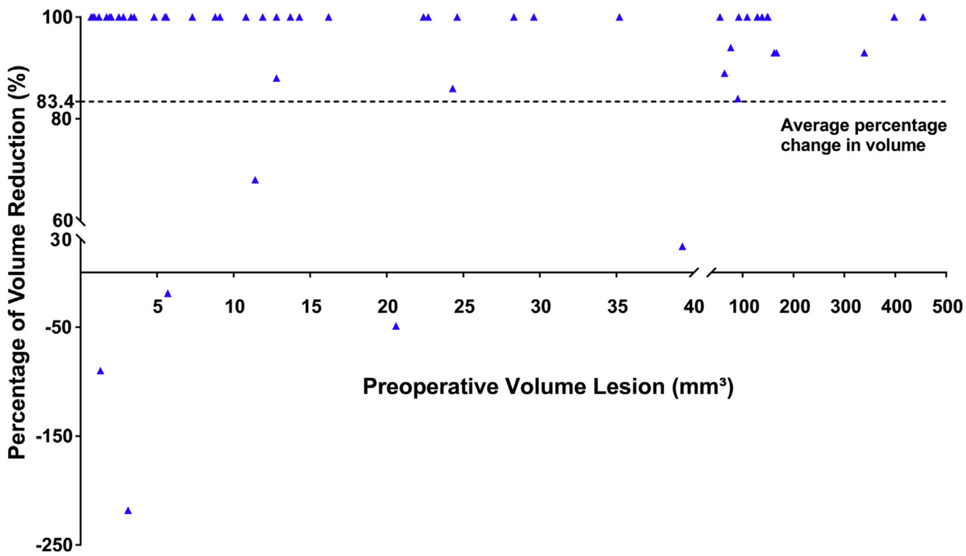

FIGURE 4 – A scatterplot of percentage change in the volume of periapical lesions at 48–67 months after root canal retreatment. The points above the x-axis represent reduction in the volume of the radiolucencies, and the points below the axis indicate enlargement in the volume. The *dotted line* shows the average percentage change in a volume of 83.4%.

reviewed 1–4 years after treatment, with an average 22-month follow-up. They reported a complete healed rate of 36% for retreatment. When the follow-up period was 4–5 years in our study, the percentage of absence of radiolucency was 76%. As shown in the previous studies, of all the teeth that ultimately healed, only 50%–70% had healed by 1 year, with the proportion increasing up to 90% by 2–4 years[9,21]. Considering the gradual periapical healing process, the European Society of Endodontology recommends assessing a lesion that has remained the same size or diminished in size until it has resolved or for a minimum period of 4 years[22]. Furthermore, in this study, all the treatments were performed by well-trained and experienced endodontic specialists with at least 5 years of experience. Torabinejad et al[20] found that an operator's training background and clinical experience significantly influence endodontic retreatment outcomes.

Apart from the teeth in which radiolucency was completely resolved, 10 teeth (17.2%) had reduced radiolucencies, and of these teeth, 80% showed a decrease in the apical lesion volume of more than 80%. In an animal study, it was demonstrated that the presence of radiolucency on CBCT scans is correlated with the severity of inflammation[23]. A significant reduction in radiolucency could represent a reduction in the infection burden in the root canal system and the achievement of minimizing the severity of apical periodontitis[24]. Biofilms in the root canal system cannot be eradicated completely with current endodontic techniques used in both primary root canal treatment and retreatment[25,26]. It could be reasonable to assume 93.1% of the teeth with complete or partial resolution of radiolucency in the present study as effective outcome cases, which meant a successful management of apical periodontitis, and no further intervention was needed[24].

The recall rate is an issue of importance for outcome studies. A low recall rate indicates a large portion of "dropouts" with probably favorable or unfavorable treatment outcomes, which may result in an underestimate or overestimate of the success rate and eventually lead to a biased invalidated outcome[1]. In outcome studies, achieving a high recall rate has always been considered as a difficult and challenging objective. In the Toronto Study on orthograde retreatment in phases 1 and 2 and phases 3 and 4, although many efforts were made to improve the recall rate, only 24%–30% of the included teeth were followed up at 4–6 years after root canal retreatment[5,6]. In the present study, 35 teeth from 30 patients were not available at hospital for follow-up, including 22 teeth from 18 patients who could not be contacted and 13 teeth from 12 patients who declined recall for personal reasons. For the latter group of patients who refused to be recalled to the hospital, telephone recall was performed by investigating the survival and function of the treated teeth to acquire more information on outcome and to minimize the effect of dropouts. All these teeth were functional and free of symptoms. However, these patients who received an incomplete review were still defined as "dropouts."

CBCT imaging, as a 3-dimensional imaging method that offers details of localized teeth and adjacent anatomy, can be a powerful tool in endodontic diagnosis, treatment planning, and follow-up[12]. Compared with periapical radiographs in identifying periapical radiolucencies, CBCT imaging is consistently more sensitive, with approximately 10%–30% higher lesion detection than that observed in periapical radiographs, resulting in a more accurate assessment of the outcomes of primary and secondary endodontic treatment[4,13,14,23]. Furthermore, the validity of apical lesion volumetric measurements based on CBCT imaging has been studied *in vitro*[15], providing a lower pressure outcome assessment dimension for evaluators. In this study, using CBCT scanning as recall evaluation choice has been weighed by its benefits against the risk of radiation exposure[27] and obtained ethical approval. Small field of view CBCT imaging was prescribed, and the exposure setting was adhered to the ALARA (as low as reasonably achievable) principle on the basis of ensuring radiograph quality[28]. Moreover, thyroid collar protection was used for all patients. However, in clinical practice, CBCT imaging should be indicated only when lower-dose conventional dental radiography cannot answer the clinical question adequately[27]. It could also be used for follow-up evaluation for the patients with preoperative CBCT data adhering to the joint position statement by the

TABLE 3 - A Summary of Bivariate Analysis for the Effects of Clinical Factors on Radiographic Outcome at the 4-year Follow-up

Factors	No. of teeth	Radiographic outcome: Absence of periapical lesion (%)	Radiographic outcome: Presence of periapical lesion (%)	P value
Tooth type				.001
Anterior	27	26 (96.3)	1 (3.7)	
Premolar	13	9 (69.2)	4 (30.8)	
Molar	18	9 (50.0)	9 (50.0)	
Sex				.211
Male	19	12 (63.2)	7 (36.8)	
Female	39	32 (82.1)	7 (17.9)	
Age				1.000
≤45 years	55	42 (76.4)	13 (23.6)	
>45 years	3	2 (66.7)	1 (33.3)	
Preoperative lesion volume				.316
≤65 mm^3	45	36 (80.0)	9 (20.0)	
>65 mm^3	13	8 (61.5)	5 (38.5)	
Complications of primary treatment				.316
Absent	45	36 (80.0)	9 (20.0)	
Present	13	8 (61.5)	5 (38.5)	
Root filling length				.060
Flush	25	22 (88.0)	3 (12.0)	
Short	3	1 (33.3)	2 (66.7)	
Long	30	21 (70.0)	9 (30.0)	
Root filling density				1.000
Satisfactory	57	43 (75.4)	14 (24.6)	
Unsatisfactory	1	1 (100.0)	0 (0.0)	
Coronal restoration				.241
Satisfactory	57	44 (77.2)	13 (22.8)	
Unsatisfactory	1	0 (0.0)	1 (100.0)	
Total	58	44	14	

American Association of Endodontists and the American Academy of Oral and Maxillofacial Radiology[27].

The same software used in our previous *in vitro* study was also used in this study for volume measurement based on CBCT data. According to the reported result that the percentage of deviation compared with the gold standard physical volume reaches up to 18%, a limit of 20% was set as the volumetric change to avoid bias[15]. In this study, the percentage volume change ranged from 19%–100%, with only 1 tooth having volume changes less than 20%. With the integration of artificial intelligence into radiography and the development of CBCT devices, it is expected that the border of the lesion can be intelligently identified to minimize deviation and to enable the 3-dimensional quantitative outcome assessment method to be less time-consuming and more practical.

In this study, only tooth type was identified as a predictor. Compared with the completely resolved rate of radiolucency of 96% in anterior teeth, the rates in premolars and molars were 24% and 49% lower, respectively (Table 3). This finding corroborated the results of several previous studies that also reported a trend of a lower healed rate in molars[29,30]. In the study by Olcay et al[30], the healed rate of mandibular molars was the lowest at 59% followed by 81% for mandibular premolars and 85% for maxillary anterior teeth. This finding might be partially explained by the diversity and complexity of root canal anatomy and treatment accessibility for operators on different tooth types. However, from a methodology aspect, the use of the tooth rather than the root as the evaluated unit may cause the risk of the presence of apical lesions to be multiplied by the number of roots in multirooted teeth, where the outcome of the tooth was assessed according to the root that had the worst treatment outcome[31]. After analyzing the raw data provided by Sjögren et al[32] using the chi-square test, no significant difference was found in the healing rate for different tooth types when the root was used as the unit of evaluation ($P = .712$).

It has been found that intraoperative complications that occurred in previous treatment, including perforation, file separation, missed canals, and aberrant anatomy, might negatively impact the outcome of secondary root canal treatment[5]. In the present study, 13 teeth had complications preoperatively, including 9 teeth with missed canals, 3 with canal transportation, and 1 with a lateral perforation. The rates of completely resolved lesions in teeth with and without complications were 62% and 80%, respectively, with a differential of 18%, and no new complications occurred during the retreatment. The identification and management of preoperative complications, especially for missing root canals and perforations, is enhanced by the equipment of CBCT imaging, operating microscopes, and bioceramics. Eventually, all 9 missed canals were relocated and treated. At recall, 7 teeth (78%) were completely healed, and 1 tooth was determined as a reduced lesion. The remaining tooth with an enlarged lesion is discussed further in the following paragraph about failure cases. One tooth with a perforation was repaired with mineral trioxide aggregate, and the absence of radiolucency was observed at recall. However, for the 3 teeth with canal transportation that could not be corrected, only 1 tooth showed lesion reduction. The other 2 teeth presented a failure outcome, which could have resulted from the negative influence of complications on infection removal in the root canal system[33].

Four teeth were extracted because of tooth fracture, and none of the 4 teeth were restored with a crown after retreatment. Two teeth were extracted before the 4-year preoperative review, 1 of which was extracted 1 year after retreatment with a reduced lesion on the radiographic examination, and the other was extracted 2 years after retreatment and had no information on the postoperative periapical status. The other 2 teeth were single-root premolars diagnosed as crown and root fracture with enlarged lesions radiographically at the 4-year review, and then extraction was recommended. In the study by Ng et al[11], when the periapical health status was used for outcome assessment, the teeth, which had no information on the periapical status at the time of extraction or were extracted for reasons not related to endodontic problems, were excluded from the analysis of outcome. Considering the extraction of root-filled teeth because of tooth fracture, Tang et al[34] concluded that the causes of potential tooth fracture are multifactorial, with the loss of tooth structure and the stresses generated during root canal and restorative procedures as possible main causes. It was difficult to determine the original causes of tooth extraction under the condition that the enlargement of radiolucency was associated with tooth fracture. In this study, the 4 extracted teeth were excluded from the outcome assessment to avoid a potential underestimation of the outcome and affect risk factor analysis.

It is widely accepted that infection remaining in the inaccessible apical areas, extraradicular infection, true radicular cysts, and foreign body reactions are the most common causes of unresolved apical periodontitis after endodontic treatment[35]. In this study, 3 teeth showed an enlarged lesion volume, and 1 tooth remained unchanged at 4 years after retreatment. All 4 teeth were functioning normally and free of symptoms. Among these teeth, 2 were molars with preoperative canal transportation, and canal patency could not be achieved during retreatment. This may hinder the elimination or dramatic reduction in apical infection and further avoid the sufficient ecologic shift to host tissue healing[2]. The other 2 teeth had sealer extrusion in retreatment. For these 4 teeth, surgical intervention was considered and recommended in subsequent planning.

In conclusion, within the limitation of this study, the 4-year outcome of endodontic retreatment was predictable, with a significant volumetric reduction in periapical radiolucencies.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ming-Ming Zhang: Investigation, Writing - original draft, Methodology. **Gao-Feng Fang:** Investigation, Writing - original draft, Data curation, Visualization. **Xiao-Tong Chen:** Data curation. **Yu-Hong Liang:** Conceptualization, Writing - review & editing, Supervision.

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Ming-Ming Zhang and Gao-Feng Fang contributed equally to this study.

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The authors deny any conflicts of interest related to this study.

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