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Original Article

Superiority of Warm Vertical Condensation in C-shaped root canals: improved periodontal health, enhanced fracture resistance, with reduced pain and secondary caries incidence

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Abstract: Objective: To compare the clinical efficacy between the methods of Cold Lateral Compaction (CLC) and Warm Vertical Condensation (WVC) in treating C-shaped root canals, focusing on periodontal health, fracture resistance, postoperative pain, and the incidence of secondary caries. Methods: This retrospective cohort study involved 229 patients treated with either CLC (n=106) or WVC (n=123) from January 2022 to December 2023. Baseline characteristics were comparable between the two groups. Clinical data on clinical efficacy, periodontal indices, fracture resistance, pain scores, and secondary caries incidence were collected and analyzed. Results: The WVC technique demonstrated superior clinical outcomes, with an effectiveness rate of 95.93% compared to 87.74% for CLC (P=0.022). Patients treated with WVC showed significantly greater improvements in periodontal indices, including reduced plaque and gingival indices, probing depth, and tooth mobility one month post-treatment (all P<0.05). Additionally, the WVC group exhibited enhanced fracture resistance, with shorter dye penetration lengths and higher compressive load capacity (P=0.004 and P=0.006, respectively). Postoperative pain was reduced in the WVC group, as indicated by lower Visual Analog Scale (VAS) scores (P=0.027). Furthermore, the incidence of secondary caries at 24 months was significantly lower in the WVC group (11.38% vs 23.58% for CLC, P=0.014). The WVC group also showed marked reductions in inflammatory markers postoperatively, including interleukin-6 (IL-6), tumor necrosis factor-α (TNF-α), interleukin-8 (IL-8), and C-reactive protein (CRP) (P<0.05). Conclusion: The WVC technique is more effective than CLC for C-shaped root canals. It not only provides superior sealing capabilities but also improves periodontal health, increases fracture resistance, reduces postoperative pain, and lowers the incidence of secondary caries.

Keywords: C-shaped root canals, warm vertical condensation, cold lateral compaction, endodontic therapy, periodontal indices, fracture resistance

Introduction

Endodontic treatment of teeth with C-shaped root canals presents unique challenges due to the complex and often convoluted canal morphology associated with these anatomical variations. Unlike conventional root canals, C-shaped canals commonly feature complex isthmuses and irregular configurations, which complicate the achievement of complete debridement and optimal obturation. Understanding the efficacy of different obturation techniques is critical to improving treatment outcomes for these cases [1, 2]. Two primary methods frequently used for obturation in such cases are Cold Lateral Compaction (CLC) and Warm Vertical Condensation (WVC), each of which possesses distinct procedural characteristics that affect their effectiveness in addressing the complexities of C-shaped root canals [3, 4].

The CLC technique, a traditional method in endodontics, utilizes lateral forces to compact gutta-percha cones within the prepared canals. This technique is favored for its simplicity and cost-effectiveness. However, its ability to adapt to the aberrant morphologies of C-shaped root canals remains a significant limitation. The

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inherent rigidity of gutta-percha under cold conditions restricts its flow, potentially resulting in voids and unfilled spaces within the canal system. These voids may serve as potential pathways for bacterial infiltration, increasing the risk of treatment failure. Moreover, the mechanical compaction involved may not adequately seal the irregularities inherent in C-shaped canals [5-7].

In contrast, the WVC technique leverages the thermoplastic properties of gutta-percha, allowing it to flow more easily and fill complex canal structures. By applying heat, the WVC method enhances the adaptability of gutta-percha, potentially improving the sealing capacity in intricate root canal systems, including those with C-shaped configurations. Studies suggest that WVC may be more effective in filling lateral canals and isthmuses, contributing to its increasing popularity among clinicians aiming for more comprehensive canal obturation [3, 8, 9].

Despite advances in endodontic instrumentation and materials, the choice of obturation technique remains a matter of debate, particularly for teeth with atypical root canal anatomies. The lack of consensus in the literature regarding the comparative efficacy of CLC and WVC techniques in treating C-shaped root canals underscores the need for comprehensive clinical evaluations [3, 10]. Studies comparing these methods can provide valuable insights into their respective impacts on treatment outcomes, including periodontal health, fracture resistance, and patient-reported discomfort.

Periodontal index levels, which serve as critical indicators of periodontal health, are essential for assessing the systemic impact of endodontic interventions. Inadequate root canal sealing can predispose patients to periapical inflammation, which often manifests as elevated periodontal indices, including increased probing depths and gingival inflammation. A reliable obturation technique that minimizes periapical inflammation may therefore have favorable effects on these indices, reducing the risk of post-treatment complications [11-13].

Another important consideration is the fracture resistance of endodontically treated teeth. The structural integrity of teeth with a C-shaped root canal is frequently compromised due to unique stress distribution patterns and thinner dentinal walls. As a result, the choice of obturation technique, which influences how stress is transferred to the surrounding tooth structure, plays a vital role in preventing fractures [4].

Pain management is a fundamental aspect of successful endodontic therapy. Postoperative pain is often influenced by the quality of obturation. Techniques that ensure thorough disinfection and effective sealing of the root canal system can help minimize postoperative discomfort by reducing residual microbial activity and periapical tissue irritation. Therefore, examining pain outcomes can provide valuable insights into the comparative effectiveness of the CLC and WVC techniques in clinical practice [14-16].

Additionally, the long-term success of root canal treatment depends largely on preventing secondary caries, which typically arise from microleakage at the tooth-restoration interface or reinfection through voids in the obturation material. Evaluating the incidence of secondary caries in teeth treated with either technique can provide valuable information about their ability to form durable and reliable seals against microbial infiltration [17-19].

The present study aims to comprehensively assess and compare the efficacy of the WVC and CLC techniques in obturating C-shaped root canals, with the hope of providing guidance for practitioners in selecting the most effective obturation technique for these challenging cases, thereby improving patient outcomes.

Methods

Case selection

This retrospective cohort study included 229 patients with chronic pulpitis and periapical periodontitis, treated at the 964th Hospital of Joint Logistic Support Force of PLA from January 2022 to December 2023. Patients treated with the CLC technique were assigned to the CLC group (n=106), while those treated with the WVC method were assigned to the WVC group (n=123). Demographic information and clinical data, including general characteristics, clinical efficacy, periodontal indices, fracture resistance, pain scores, and the incidence of secondary caries, were extracted from the hospital's medical records system. The primary aim of this study was to evaluate and compare the effectiveness of the WVC and CLC methods in obturating C-shaped root canals and to explore their impact on periodontal health, fracture resistance, postoperative pain, and the occurrence of secondary caries.

Inclusion criteria for the study were as follows: 1) Patients with radiographic evidence of fully developed root apices, accompanied by periapical bone destruction or lateral root shadowing; 2) Patients with C-shaped canals who had undergone tooth extraction due to periodontal disease, with detectable deep carious lesions or restorations in the affected tooth; 3) Patients with a single affected tooth; and 4) Patients with complete clinical documentation.

Exclusion criteria included: 1) Patients with a history of previous endodontic treatment; 2) Patients with calcified root canals or significant root resorption; 3) Patients with tooth fractures; 4) Patients with caries extending into the pulp chamber; 5) Patients with comorbidities, such as malignancy, severe infections, or coagulopathies; 6) Patients with immune system disorders; and 7) Patients with psychiatric conditions or cognitive impairments that hinder effective communication.

The study was approved by the Institutional Review Board and Research Ethics Committee of the 964th Hospital of Joint Logistic Support Force of PLA. As a retrospective study utilizing only de-identified patient data, which posed no risk to patient care, an informed consent waiver was granted. This waiver was authorized in accordance with the regulatory and ethical standards for retrospective research.

Intervention method

In the CLC group, patients underwent obturation of C-shaped root canals using the CLC technique. The procedure began with routine preoperative radiographs, followed by access cavity preparation, pulp extirpation, working length determination, and conventional canal preparation and disinfection. A spiral delivery instrument was used to introduce the root-end filling material (sealer) into the canal. The disinfected master gutta-percha cone was then coated with a thin layer of sealer and carefully inserted into the canal, stopping 3-5 mm short of the apex to prevent excessive sealer accumulation. Lateral compaction was achieved with a condenser [Shanghai Kangqiao Dental Medical Instrument Factory, model: 003-3413 (KRCPS40)]. Additional auxiliary gutta-percha cones were added, and the compaction process was repeated until the canal was tightly filled. A post-treatment radiograph was then taken to verify the adequacy of the obturation.

In the WVC group, obturation of the C-shaped root canal was performed using the WVC technique with thermoplasticized gutta-percha. Canal preparation followed conventional methods, similar to the CLC group. Initially, the master gutta-percha cone was coated with AH Plus sealer and inserted to the working length. A heated carrier was then used to remove excess gutta-percha beyond the canal orifice. A large vertical compactor [Shanghai Kangqiao Dental Medical Instrument Factory, model: 003-4014 (KRCP1/3)] was employed to apply uniform pressure repeatedly to the apical third of the canal. Afterward, the heated carrier was reinserted to remove approximately 3 mm of softened gutta-percha, and a medium vertical compactor (Obtura Spartan, USA) was used for further compaction. This process was repeated until the gutta-percha was compacted approximately 4 mm short of the working length, ensuring a tight seal at the apical end. Finally, a heated gutta-percha backfiller was used to create contact with the gutta-percha in the canal and to apply incremental pressure, backfilling the canal up to the orifice.

Data collection and outcome measurements

Data collection involved a comprehensive review of demographic and clinical information, including general characteristics, clinical efficacy, periodontal indices, fracture resistance, pain scores, incidence of secondary caries, and inflammatory markers. Both preoperative and one-month postoperative assessments were conducted to evaluate periodontal indices, which included the Plaque Index (PLI), Gingival Index (GI), Periodontal Pocket Depth (PD), and Mobility Degree (MD).

Primary outcomes: Clinical Efficacy Evaluation; Anti-fracture Capability.

Secondary outcomes: Levels of Periodontal Indices; Visual Analog Scale (VAS) Scores; Occurrence of Secondary Caries; Inflammatory Markers.

Clinical efficacy evaluation: In order to assess the clinical efficacy of both treatment groups two years post-intervention, the following evaluation criteria were used.

Marked effectiveness: Defined by normal radiographic findings, complete resolution of clinical symptoms, full recovery of periapical tissues, and optimal occlusal function.

Effective: Indicated by a significant reduction in radiographic translucency, substantial improvement in clinical symptoms, and partial recovery of occlusal function and periapical tissues.

Ineffective: Defined by no significant change or an increase in radiographic translucency, persistent clinical symptoms, and inadequate occlusal function.

The overall effectiveness rate was calculated using the formula: [(Number of cases with marked effectiveness + Number of effective cases)/Total number of cases] × 100%.

Levels of periodontal indices: Periodontal indices were assessed for all patients both preoperatively and one month after treatment. The indices measured included the Plaque Index (PLI), Gingival Index (GI), Periodontal Pocket Depth (PD), and Mobility Degree (MD).

PLI: Scores range from 0 to 3. A score of 0 indicates the absence of plaque at the marginal gingiva; 1 represents a thin film of plaque visible upon scraping the marginal gingiva with a probe; 2 denotes moderate plaque on marginal or interproximal surfaces; and 3 signifies heavy plaque accumulation in the gingival sulcus or on the marginal gingiva and interproximal areas.

GI: Scores range from 0 to 3. A score of 0 denotes healthy gingiva; 1 indicates mild inflammation with slight color change and no swelling or bleeding on probing; 2 reflects moderate inflammation with redness, edema, and bleeding on probing; and 3 represents severe inflammation with redness, swelling, and spontaneous bleeding.

PD: This is measured as the distance from the gingival margin to the base of the gingival sulcus or periodontal pocket.

MD: Scores range from 0 to 3. A score of 0 indicates no mobility; 1 denotes first-degree mobility, with movement exceeding the normal physiological range but less than 1 mm, observed only in the buccolingual or labiolingual direction; 2 signifies second-degree mobility, with movement ranging from 1 to 2 mm in both the buccolingual and mesiodistal directions; and 3 represents third-degree mobility, with movement greater than 2 mm in buccolingual, mesiodistal, and vertical directions [13].

Anti-fracture capability: To compare apical microleakage between groups, the dye penetration method was employed. Teeth were immersed in methyl salicylate until transparent, after which they were removed for analysis. Photographs of the four surfaces of each transparent tooth were captured under a microscope, and the average dye penetration length was calculated. For evaluating root fracture resistance, after the dye staining process, a universal testing machine was used to measure the maximum load force at the point of fracture, which indicates the tooth's compressive load capacity [20].

VAS scores: Pain levels were assessed using VAS scores both preoperatively and one month post-treatment to determine the degree of periodontal pain experienced by patients. The VAS is a 10-cm scale used to measure pain intensity at rest, during daily activities, and at night. Higher scores indicate more severe pain. Patients marked their pain intensity on a line ranging from 0 ("no pain"), to 10 ("worst imaginable pain"). The distance from '0' to the patient's mark was measured for analysis. This scale has shown reliability, with a Cronbach's alpha coefficient of 0.86 [21].

Occurrence of secondary caries: Secondary caries were diagnosed based on the following criteria: 1) discoloration of tooth tissue at the restoration margins; 2) a gap between the restoration and the tooth, with softened tooth tissue detectable; and 3) development of caries on the remaining tooth surfaces post-restoration. Follow-up evaluations were performed at 3, 6, 12, and 24 months after treatment using visual inspection, probing, and radiographic

Table 1. Baseline characteristics of participants

Parameters	CLC group (n=106)	WVC group (n=123)	t/X^2	P
Age (years)	40.84±3.28	41.16±3.34	0.722	0.471
Gender (Male/Female)	58 (54.72%)	66 (53.66%)	0.026	0.873
Body Mass Index (kg/m^2)	24.33±5.92	24.56±5.34	0.309	0.757
Drinking history [n (%)] (Y/N)	35 (33.02%)	38 (30.89%)	0.118	0.731
Smoking history [n (%)] (Y/N)	39 (36.79%)	43 (34.96%)	0.083	0.773
Employment [n (%)] (Y/N)	78 (73.58%)	93 (75.61%)	0.123	0.725
Education level [n/(%)]			0.192	0.979
Illiterate [n (%)]	2 (1.89%)	3 (2.44%)		
Primary Education [n (%)]	21 (19.81%)	26 (21.14%)		
Secondary Education [n (%)]	48 (45.28%)	53 (43.09%)		
University degree [n (%)]	35 (33.02%)	41 (33.33%)		
Marital status [n (%)]			0.225	0.893
Unmarried [n (%)]	31 (29.25%)	33 (26.83%)		
Married with spouse [n (%)]	64 (60.38%)	78 (63.41%)		
Divorced or widowed [n (%)]	11 (10.38%)	12 (9.76%)		
Disease duration (years)	5.36±1.52	5.57±1.56	1.040	0.300
Root length (mm)	13.16±0.77	13.21±0.76	0.469	0.639
C-shaped canal configuration [n (%)]			0.125	0.939
C1 type [n (%)]	19 (17.92%)	20 (16.26%)		
C2 type [n (%)]	64 (60.38%)	75 (60.98%)		
C3 type [n (%)]	23 (21.70%)	28 (22.76%)		

Note: CLC, Cold Lateral Compaction; WVC, Warm Vertical Condensation.

examination to detect any microgaps in the restoration.

Inflammatory markers: Inflammatory markers were compared between the two patient groups both preoperatively and one week after surgery. Fasting venous blood samples were collected at both time points, centrifuged at 3,000 r/min to extract the supernatant, and analyzed for levels of interleukin-6 (IL-6), tumor necrosis factor-α (TNF-α), interleukin-8 (IL-8), and C-reactive protein (CRP). Measurements were performed using a Mindray BS-800 fully automatic biochemical analyzer in conjunction with enzyme-linked immunosorbent assay (ELISA). Reagent kits provided by Beijing Sinovac Biotech Co., Ltd. were used according to the manufacturer's instructions.

Statistical methods

Data analysis was performed using SPSS 29.0 statistical software (SPSS Inc., Chicago, IL, USA). Categorical data were presented as [n (%)]. The chi-square test was used when the sample size was ≥40 and the expected frequency (T) was ≥5, with the test statistic χ^2. When the sample size was ≥40 but 1≤T<5, the chi-square test was adjusted using a correction formula. For sample sizes <40 or when T<1, Fisher's exact test was applied.

For continuous variables, the normality of the data was assessed using the Shapiro-Wilk test. Normally distributed data were presented as means ± standard deviations ($\bar{x}$ ± s), while non-normally distributed data were analyzed using the Wilcoxon rank-sum test and presented as medians with interquartile ranges [median (25th percentile, 75th percentile)]. A *P*-value of <0.05 was considered statistically significant. Correlation analysis was conducted using Pearson's correlation coefficient for continuous variables and Spearman's rank correlation for categorical variables.

Results

Baseline characteristics

The study included a total of 229 participants, who were divided into two groups: CLC (n=106) and WVC (n=123). As shown in **Table 1**, the baseline characteristics of participants were

Table 2. Comparison of clinical efficacy between the two groups at the 2-year follow-up

Parameters	CLC group (n=106)	WVC group (n=123)	X^2	P
Marked Effectiveness [n (%)]	59 (55.66%)	69 (56.10%)		
Effective [n (%)]	34 (32.08%)	49 (39.84%)		
Ineffective [n (%)]	13 (19.70%)	5 (4.07%)		
Overall effectiveness rate [n (%)]	93 (87.74%)	118 (95.93%)	5.285	0.022

Note: CLC, Cold Lateral Compaction; WVC, Warm Vertical Condensation.

Table 3. Comparison of periodontal index levels between the two groups before and one month after treatment

Parameters		CLC group (n=106)	WVC group (n=123)	t	P
PLI (points)	Preoperative (points)	2.46±0.34	2.45±0.40	0.286	0.775
	1 month postoperative (points)	1.38±0.29	1.31±0.12	2.214	0.028
GI (points)	Preoperative (points)	2.85±0.47	2.83±0.59	0.219	0.827
	1 month postoperative (points)	1.43±0.26	1.33±0.31	2.439	0.015
PD (mm)	Preoperative (points)	5.79±1.04	5.77±1.03	0.107	0.915
	1 month postoperative (points)	4.92±0.77	4.72±0.68	2.072	0.039
MD (points)	Preoperative (points)	2.10±0.38	2.11±0.52	0.225	0.822
	1 month postoperative (points)	1.83±0.25	1.72±0.33	2.782	0.006

Note: CLC, Cold Lateral Compaction; WVC, Warm Vertical Condensation; PLI, plaque index; GI, gingival index; PD, probing depth; MD, mobility degree.

comparable between the two groups, with no significant differences in age, gender distribution, or body mass index (P>0.05). Similarly, there were no significant differences in drinking and smoking history, employment status, education level, or marital status (P>0.05). The mean disease duration was 5.36±1.52 years in the CLC group and 5.57±1.56 years in the WVC group (P=0.300). Additionally, root length (13.16±0.77 mm vs 13.21±0.76 mm; P=0.639) and C-shaped canal configuration types (P=0.939) were also comparable between the two groups. These findings indicate that baseline characteristics were homogeneously distributed, minimizing potential confounding factors in the subsequent comparison of treatment outcomes.

Clinical efficacy

Two years post-treatment, the overall effectiveness rate was significantly higher in the WVC group (95.93%) compared to the CLC group (87.74%), with a statistically significant difference (X^2=5.285, P=0.022). The distribution of marked effectiveness was similar between the groups, with 55.66% in the CLC group and 56.10% in the WVC group. However, a noticeable difference was observed in the ineffectiveness rate, with the CLC group showing a higher rate (19.70%) compared to the WVC group (4.07%). The effective outcomes were slightly more frequent in the WVC group (39.84%) than in the CLC group (32.08%). These results suggest that the WVC method may offer superior clinical efficacy compared to the CLC method over a two-year period. A summary of these findings is presented in **Table 2**.

Periodontal indices

In the WVC group, the PLI decreased from 2.45±0.40 to 1.31±0.12, while in the CLC group, it decreased from 2.46±0.34 to 1.38±0.29. The difference between groups postoperatively was statistically significant (P=0.028) (**Table 3**). Similarly, the GI showed a significant reduction, with postoperative scores of 1.33±0.31 in the WVC group and 1.43±0.26 in the CLC group (P=0.015). Probing depth (PD) also improved with postoperative measurements of 4.72±0.68 mm for the WVC group and 4.92±0.77 mm for the CLC group (P=0.039). Moreover, the MD showed a more pronounced reduction in the WVC group, decreasing to 1.72±0.33 compared to 1.83±0.25 in the CLC group (P=0.006). Preoperative values for PLI, GI, PD, and MD showed no significant differences between the two groups, confirming homogeneity at baseline. These results indi-

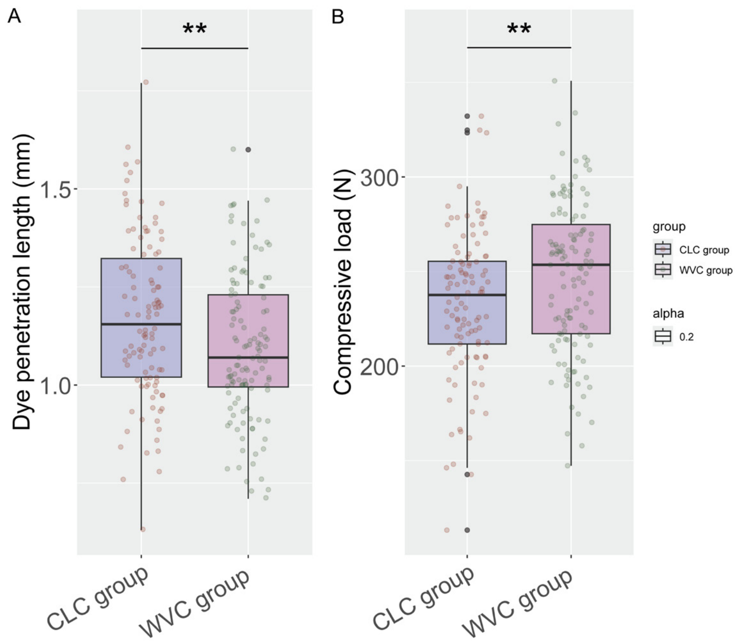

Figure 1. Comparison of anti-fracture capability between the two groups. A. Dye penetration length (mm); B. Compressive load (N). Note: CLC, Cold Lateral Compaction; WVC, Warm Vertical Condensation; **: P<0.01.

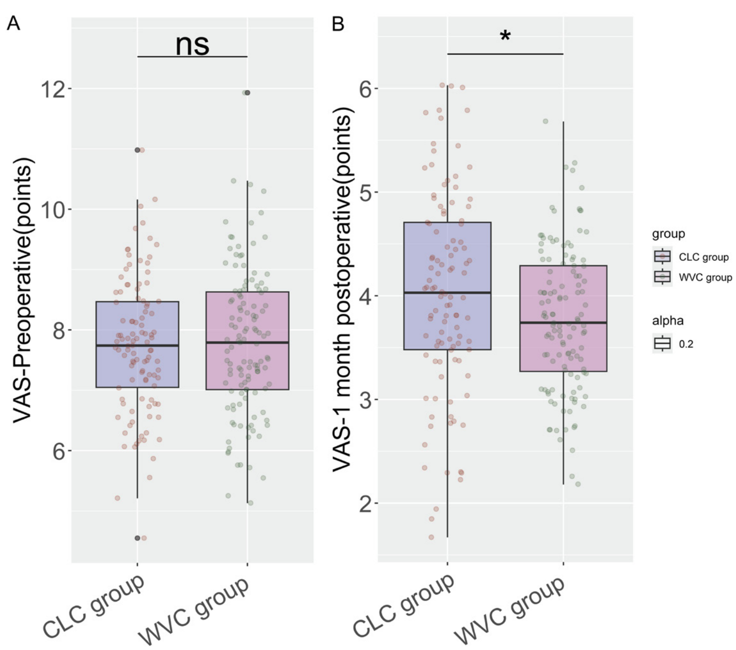

Figure 2. Comparison of VAS scores between the two groups. A. Preoperative scores (points); B. One month postoperative scores (points). Note: CLC, Cold Lateral Compaction; WVC, Warm Vertical Condensation; VAS, Visual Analogue Scale; ns: P>0.05; *: P<0.05.

cate that the WVC technique offers superior improvements in periodontal health one month following treatment.

Anti-fracture capability

The WVC group showed a significantly shorter dye penetration length (1.09±0.19 mm) compared to the CLC group (1.17±0.21 mm), with a statistically significant difference (t=2.913, P=0.004) (**Figure 1**). Additionally, the WVC group withstood a greater compressive load, with an average force of 247.34±40.15 N compared to 232.77±38.96 N in the CLC group, which was also statistically significant (t=2.776, P=0.006). These findings suggest that the WVC technique may enhance the anti-fracture capability of treated C-shaped root canals, potentially offering superior structural integrity over the CLC method.

VAS scores

The WVC group demonstrated a lower mean VAS score (3.77±0.69) compared to the CLC group (4.03±0.98), with a statistically significant difference (t=2.230, P=0.027) (**Figure 2**). No significant difference was observed between the groups in preoperative VAS scores (WVC: 7.80±1.20, CLC: 7.74±1.12; t=0.397, P=0.692), indicating comparable baseline pain levels prior to treatment. These findings suggest that the WVC technique may be more effective in reducing post-treatment pain compared to the CLC method.

Incidence of secondary caries

At 24-month follow-up, the WVC group showed a significantly lower incidence of secondary caries (11.38%) compared to the CLC group (23.58%), with statistical significance (X^2=6.000, P=0.014) (**Table 4**). While no significant differences were observed between the groups at the 3-month, 6-month, and 12-month follow-ups (P=0.463, P=0.195, and

Table 4. Comparison of secondary caries incidence between the two groups

Parameters	CLC group (n=106)	WVC group (n=123)	X^2	P
3 months postoperative [n (%)]	1 (0.94%)	0 (0.00%)	0.532	0.463
6 months postoperative [n (%)]	3 (2.83%)	0 (0.00%)	1.678	0.195
12 months postoperative [n (%)]	8 (7.55%)	6 (4.88%)	0.707	0.401
24 months postoperative [n (%)]	25 (23.58%)	14 (11.38%)	6.000	0.014

Note: CLC, Cold Lateral Compaction; WVC, Warm Vertical Condensation.

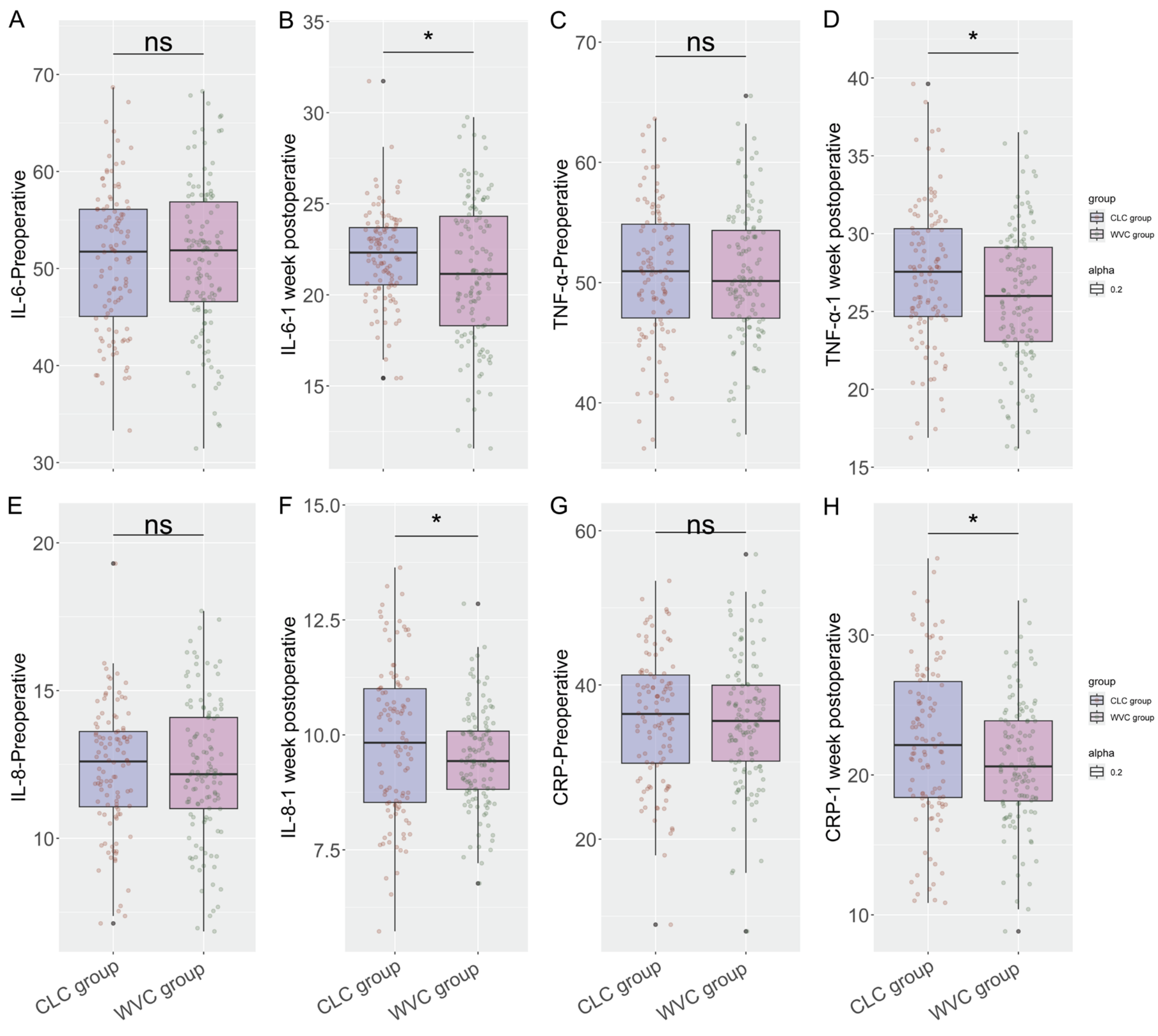

Figure 3. Comparison of inflammatory markers between the two groups. A. Preoperative IL-6 (ng/L); B. IL-6 at 1 week postoperative (ng/L); C. Preoperative TNF-α (ng/mL); D. TNF-α at 1 week postoperative (ng/mL); E. Preoperative IL-8 (ng/L); F. IL-8 at 1 week postoperative (ng/L); G. Preoperative CRP (mg/L); H. CRP at 1 week postoperative (mg/L). Note: CLC, Cold Lateral Compaction; WVC, Warm Vertical Condensation; IL-6, interleukin-6; TNF-α, tumor necrosis factor-α; IL-8, interleukin-8; CRP, C-reactive protein. ns: P>0.05; *: P<0.05.

P=0.401, respectively), there was a clear trend toward a lower incidence of secondary caries in the WVC group, which became pronounced at the 24-month mark. These findings suggest that the WVC technique may provide long-term benefits in preventing secondary caries.

Inflammatory markers

The WVC group exhibited significantly lower levels of IL-6 (21.28±3.96 ng/L) compared to the CLC group (22.16±2.55 ng/L) (t=2.022, P=0.044) (**Figure 3**). Similarly, TNF-α levels

Table 5. Comparison of adverse events between the two groups one month after surgery

Parameters	CLC group (n=106)	WVC group (n=123)	X^2	P
Abnormal mastication [n (%)]	3 (2.83%)	2 (1.63%)		
Fistula [n (%)]	1 (0.94%)	0 (0.00%)		
Increased craze lines [n (%)]	1 (0.94%)	0 (0.00%)		
Root bifurcation [n (%)]	1 (0.94%)	0 (0.00%)		
Increased shadow at the tooth apex [n (%)]	2 (1.89%)	0 (0.00%)		
Gingival pain and swelling [n (%)]	2 (1.89%)	1 (0.81%)		
Total incidence rate [n (%)]	10 (9.43%)	3 (2.44%)	5.203	0.023

Note: CLC, Cold Lateral Compaction; WVC, Warm Vertical Condensation.

were significantly reduced in the WVC group (25.94±4.36 ng/mL) compared to the CLC group (27.36±4.51 ng/mL) (t=2.405, P=0.017). IL-8 levels were also lower in the WVC group (9.48±1.05 ng/L) than in the CLC group (9.86±1.67 ng/L), with a statistically significant difference (t=2.025, P=0.044). Furthermore, postoperative CRP levels were significantly lower in the WVC group (20.86±4.39 mg/L) than in the CLC group (22.31±5.69 mg/L), with a pronounced reduction observed (t=2.134, P=0.034). Preoperative inflammatory marker levels were comparable between the two groups, indicating similar baseline conditions. These results suggest that the WVC technique may provide superior short-term reductions in postoperative inflammation compared to the CLC method.

Adverse events

The overall incidence rate of adverse events was significantly lower in the WVC group (2.44%) compared to the CLC group (9.43%) (X^2=5.203, P=0.023) (**Table 5**). Specific adverse events, including abnormal mastication, fistula formation, increased craze lines, root bifurcation, increased shadow at the tooth apex, and gingival pain and swelling, were observed at markedly lower frequencies in the WVC group.

Discussion

The present study provides a comprehensive evaluation of the efficacy of the WVC technique compared to the CLC method for the obturation of C-shaped root canals. The superior clinical efficacy observed with the WVC technique can likely be attributed to its thermoplasticity and enhanced adaptability to the complex morphology of C-shaped root canals. The WVC process enables better adaptation of thermoplasticized gutta-percha, which facilitates more effective filling of irregular canal spaces and intricate anatomical features. The application of heat softens the gutta-percha, allowing it to flow into accessory canals and lateral intricacies that may be difficult to reach with colder, more rigid methods. In contrast to the CLC technique, which relies on mechanical condensation, the WVC method ensures a more homogenous obturation, contributing to the reduced occurrence of residual voids-potential sites for bacterial infiltration and reinfection [22-24].

Our findings suggest that improvements in periodontal health indices, lower pain scores, and reduced incidence of secondary caries observed in the WVC group may stem, in part, from this superior sealing capability. The WVC technique achieves a dense root canal filling with minimal microleakage, a critical factor for long-term endodontic success. The use of heat not only enhances the effectiveness of the sealing but also ensures a tighter adaptation to canal walls, thereby reducing gap formation. This, in turn, minimizes the potential for bacterial ingress and subsequent periodontal inflammation [3, 25].

Further analysis of the periodontal index results indicates that the reductions in PLI, GI, probing depth, and tooth mobility in the WVC group suggest a link between the method of canal obturation and systemic periodontal outcomes. The thermal components of the WVC technique may indirectly promote healing by enhancing obturation quality, thereby minimizing the exposure of periapical tissues to potential irritants post-treatment. This reduction in microbial presence likely fosters a more favorable healing environment, thereby alleviating the inflammatory burden on surrounding periodontal structures [26, 27].

Similarly, the decrease in inflammatory markers such as IL-6, TNF-α, IL-8, and CRP in the WVC group further reinforces the hypothesis that the high-quality seal provided by the WVC technique reduces bacterial proliferation and endotoxin penetration. Consequently, the reduction in inflammation could help explain the favorable outcomes observed in periodontal tissues and the overall improvement in patient comfort.

Fracture resistance is another critical factor in the context of endodontically treated teeth, particularly those with C-shaped canals, which are often characterized by thinner dentin walls and unique stress distribution patterns. Our findings reveal that the WVC technique provided enhanced compressive load resistance, likely due to the more uniform distribution of the filling material and the absence of internal gaps that could act as stress concentrators. The increased contact surface area between the canal walls and the thermoplasticized gutta-percha in the WVC group may facilitate better stress distribution across the tooth structure, thereby strengthening the tooth against functional forces and reducing the risk of fracture [22, 28, 29].

Pain perception, as measured by VAS scores, showed greater improvement in the WVC group post-treatment. This could be attributed to the reduced postoperative inflammatory response resulting from superior canal disinfection and sealing. Moreover, the WVC technique likely minimizes thermal and mechanical irritation to the surrounding periodontal ligament, a common cause of postoperative pain. This is particularly relevant, as techniques like CLC, which create and condense a rigid gutta-percha core, may induce more pronounced irritation [30, 31].

The significant reduction in the incidence of secondary caries within the WVC group, particularly at the 24-month follow-up, further supports the concept that a better-sealed root canal environment offers protection against new carious lesions-either at the restoration interface or in adjacent structures. This is likely due to the enhanced sealing ability of the WVC technique, which minimizes microleakage-related carious initiation by creating a robust barrier against oral microbial flora and their metabolic byproducts [32, 33].

Finally, the differences in adverse events between the two groups emphasize the clinical advantages of the WVC technique. Reduced complications, such as fistula formation, increased craze lines, and abnormal mastication, could be indicative of the WVC technique's ability to maintain the structural integrity of the tooth while ensuring a more complete and secure obturation. The lower incidence of root bifurcation and apical shadowing may also reflect better stress management within the root following obturation [34].

While this study provides valuable insights into the comparative efficacy of the WVC and CLC techniques for C-shaped root canals, several limitations must be acknowledged when interpreting these findings. The relatively small sample size may limit the generalizability of our results to broader populations, highlighting the need for larger studies to confirm these outcomes across diverse demographic groups. Although the follow-up period was sufficient to observe initial outcomes, it may not fully capture long-term efficacy or late-onset complications, emphasizing the importance of extended follow-up periods for assessing sustained benefits. The reliance on subjective measures, such as pain perception, introduces variability, as individual responses can differ significantly; incorporating more objective assessments could provide more consistent data. Additionally, despite efforts to minimize operator variability, differences in practitioner expertise and experience with each technique may influence the results. Standardized training protocols could mitigate this effect. Lastly, as a retrospective study, inherent biases in data collection and patient selection may affect the validity of the results. Addressing these limitations in future research will be essential for strengthening the current findings and further validating the advantages of the WVC technique in clinical practice.

Conclusion

In conclusion, the WVC technique outperforms the CLC method due to its ability to achieve a more effective seal, enhanced structural integrity, and a more controlled inflammatory response. These advantages contribute to improved periodontal health, better pain management, and a reduced incidence of secondary caries. The application of heat during the WVC process enables a tight, adaptive fill that minimizes voids and related complications, thereby promoting overall tooth health. These findings underscore the importance of selecting an appropriate obturation technique in endodontic therapy, especially for complex canal systems like C-shaped canals, where the WVC technique offers distinct advantages that can significantly influence long-term clinical outcomes. Future studies should aim to further elucidate the molecular and mechanical interactions associated with these techniques to refine and enhance endodontic therapeutic strategies.

Disclosure of conflict of interest

None.

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