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META-ANALYSIS

Three-dimensional Filling Quality of Cold Lateral Versus Warm Vertical Condensation: A Micro-CT and CBCT-based Systematic Review and Meta-analysis

Mahmood DASHTI,[1] Niloofar GHADIMI,[2*] Turgut Yağmur YALÇIN,[3] Houyar ZAHMATKESH,[4] Kaan ORHAN,[5,6,7] Shahryar IRANNEJADRANKOUHI,[8] Zohaib KHURSHID,[9,10] Muhammad Sohail ZAFAR[11,12,13]

[1]Dentofacial Deformities Research Center, Research Institute of Dental Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran
[2]Department of Oral and Maxillofacial Radiology, Dental School, Islamic Azad University of Medical Sciences, Tehran, Iran
[3]Department of Endodontics, Faculty of Dentistry, İstanbul University, İstanbul, Türkiye
[4]Faculty of Dentistry, Tehran University of Medical Sciences, Tehran, Iran
[5]Department of Dento-Maxillofacial Radiology, Faculty of Dentistry, Ankara University, Ankara, Türkiye
[6]Ankara University Medical Design Application and Research Center (MEDITAM), Ankara, Türkiye
[7]Department of Oral Diagnostics, Faculty of Dentistry, Semmelweis University, Budapest, Hungary
[8]Dental School, Alborz University of Medical Sciences, Karaj, Iran
[9]Department of Prosthodontics and Dental Implantology, King Faisal University, Al-Ahsa, Saudi Arabia
[10]Center of Excellence for Regenerative Dentistry, Department of Anatomy, Faculty of Dentistry, Chulalongkorn University, Bangkok, Thailand
[11]Department of Clinical Sciences, College of Dentistry, Ajman University, Ajman, United Arab Emirates
[12]Center of Medical and Bio-allied Health Sciences Research, Ajman University, Ajman, United Arab Emirates
[13]Faculty of Dentistry, University of Jordan, Amman, Jordan

***The current affiliation of the author:** *Dental Material Research Center, TeMS.C., Dental School, Azad University of Medical Sciences, Tehran, Iran*

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Address for correspondence:
Mahmood Dashti
Dentofacial Deformities Research Center, Research Institute of Dental Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran
E-mail: dashti.mahmood72@gmail.com

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ABSTRACT

This systematic review and meta-analysis compared the efficacy of cold lateral condensation (CLC) and warm vertical condensation (WVC) in endodontic obturation. The primary focus was to evaluate three-dimensional (3D) obturation quality, including void volume, gutta-percha adaptation, and filling completeness, using Micro-Computed Tomography (Micro-CT) and Cone-Beam Computed Tomography (CBCT). A systematic search was conducted in PubMed, Embase, Scopus, and Web of Science up to December 2024 following PRISMA guidelines. Studies were included if they had compared CLC and WVC using Micro-CT or CBCT imaging and reported quantitative outcomes on gutta-percha filling and void volume. A random-effects meta-analysis was performed because of high heterogeneity (I^2=80%), with standardized mean differences (SMD) and 95% confidence intervals (CIs) calculated. Twelve studies were included in the review, with five contributing to the meta-analysis. WVC showed superior obturation quality along the full canal length (SMD=-2.19; 95% CI: -3.78 to -0.60; p=0.02). However, in the apical third, the difference was not statistically significant (SMD=-0.79; 95% CI: -1.92 to 0.35; p=0.13). While WVC offered superior adaptation and fewer voids, it also presented a higher risk of sealer extrusion. CLC, while cost-effective and widely used, exhibited more voids and poorer adaptation, particularly in complex canals. However, substantial heterogeneity (I^2=80-85%) among included studies limits confidence in these pooled estimates. WVC achieves superior obturation quality along the full length; however, the evidence remains inconclusive for the apical third, reflecting uncertainty in this anatomically complex region. High study heterogeneity underscores the need for methodological standardization. Given the high heterogeneity and methodological variation among included studies, including studies using alternative models or techniques, the findings should be interpreted with caution and serve as a basis for future standardized research.

Keywords: CBCT, cold lateral condensation, endodontics, micro-CT, obturation, warm vertical condensation

HIGHLIGHTS

- Warm vertical condensation achieved higher three-dimensional filling quality than cold lateral condensation along the full canal length.
- No clear difference was found between techniques in the apical third because of methodological variability.
- Micro CT studies showed more detailed detection of voids compared with CBCT, contributing to heterogeneity.
- Two studies using alternative models or techniques caused considerable variation in pooled outcomes.
- The findings highlight the need for standardized protocols in future research on obturation techniques.

INTRODUCTION

After the root canal system has been cleaned and shaped by endodontic therapy, three-dimensional (3D) obturation is used to create a tight, hermetic seal that completely fills the root canal space and extends as close to the cement-dentinal junction as feasible. The eventual goal is to eradicate as many microorganisms as possible (1, 2). A perfect filling for a root canal should fill the whole root canal system in three dimensions and make a uniform, homogenous substance (1). While the differences in obturation quality between these techniques have been discussed in prior literature, this review aims to synthesise quantitative 3D volumetric data using advanced imaging modalities, thereby providing methodological insight rather than direct clinical outcome evaluation.

A single gutta-percha (GP) cone with sealer is placed into the prepared root canal using the cold lateral condensation (CLC) technique, a conventional procedure that is frequently taught in undergraduate dental programmes. Secondary GP cones are then added and compacted with a spreader. The sealant and frictional grip hold the cones together (3–5). This method is used due to its inexpensive cost and accurate positioning of GP within the canal, despite the fact that it takes a lot of time (4, 6). The final filling, however, is not uniform; it is made up of several compacted GP cones, with the sealer taking up the majority of the gaps between them (7).

Schilder developed the warm vertical compaction (WVC) technique in the 1967s to improve root canal-wall adaptability (8). The WVC method involves heating the GP until it softens and changes phase, allowing it to conform to the prepared root canal wall. This method uses more heated GP and less sealer, thus any brand of sealer can be utilised (9). The WVC technique is associated with better adaptation to the canal wall. However, this technique is time-consuming, responsible for the sealer's apical extrusion, leading to post-operative pain (10).

In parallel to these technical considerations, it is important to recognise that obturation quality is a surrogate outcome, and its direct correlation with clinical success remains uncertain. With increased operator experience, control of heated gutta-percha has improved, leading to reduced procedure time and more consistent obturation outcomes (11). Generally, the WVC technique needs a lower proportion of sealer than the cold filling technique. Recent studies, including work by Camilleri (9), have debated the compatibility of WVC with hydraulic calcium silicate cements (bioceramic sealers), suggesting that this combination may affect obturation outcomes differently compared to traditional sealers.

Micro-CT is a cutting-edge technique for analysing internal tooth anatomy (12). It makes it possible to assess root canal geometry both before and after instrumentation using criteria such apical transportation, centring ratio, volume changes, cross-sectional shape, taper, and overall anatomical structure (12–14). Micro-CT's 3D imaging capability involves acquiring 2D X-ray projections that are reconstructed into a detailed 3D image (15). A single initial scan is often sufficient for assessing volume changes after root canal shaping (16).

The extraoral imaging technique Cone-Beam Computed Tomography (CBCT) creates three-dimensional scans of the orofacial skeleton (17). It successfully gets over the drawbacks of traditional radiography, including anatomical superimposition and image distortion. (18, 19) CBCT offers several benefits, including fast data acquisition (20, 21), making it a widely used tool in clinical practice and endodontic research. It is particularly valuable for analysing root canal morphology, fractures, volume changes, surface area, 3D root canal axis, thickness, surface convexity, and structure model index (22, 23). However, while CBCT delivers clear and detailed anatomical images (22), its resolution is lower than that of Micro-CT, which can pose challenges for research requiring high levels of data accuracy (24).

Both Micro-CT and CBCT present 3D images with accurate measurements, enabling detailed views and efficient identification of anatomical complexities. They are superior for evaluating and assessing canal preparation quality as well as aiding in sample selection. However, compared to Double Digital methods, both Micro-CT and CBCT require greater radiation exposure, longer time, and more complex procedures (25).

While both modalities provide 3D imaging, Micro-CT is a research tool not used in patient care, whereas CBCT is clinically applicable. Micro-CT delivers higher-resolution imaging

TABLE 1. Search strategy specific for each database

Database	Keyword	Result
PubMed	((("Warm Vertical Compaction" OR "Vertical Compaction" OR " Warm Vertical Condensation" OR "Vertical Condensation" OR "Thermoplasticized" OR "Carrier-Based") AND ("Cold Lateral Compaction" OR "Cold Lateral Condensation" OR "Lateral Compaction" OR "Lateral Condensation")) AND ("Root Canal Filling" OR "Gaps" OR "Gap" OR "Voids" OR "Void" OR "Empty Spaces" OR "Empty Space" OR "Quality")) AND ("Microcomputed tomography" OR "Micro-CT" OR "MicroCT" OR "CBCT" OR "cone beam computed tomography")	11
Embase	('Warm Vertical Compaction' OR 'Vertical Compaction' OR 'Warm Vertical Condensation' OR 'Vertical Condensation' OR 'Thermoplasticized' OR 'Carrier-Based') AND ('Cold Lateral Compaction' OR 'Cold Lateral Condensation' OR 'Lateral Compaction' OR 'Lateral Condensation') AND ('Root Canal Filling' OR 'Gaps' OR 'Gap' OR 'Voids' OR 'Void' OR 'Empty Spaces' OR 'Empty Space' OR 'Quality') AND ('Microcomputed tomography' OR 'Micro-CT' OR 'MicroCT' OR 'CBCT' OR 'cone beam computed tomography')	11
Scopus	(TITLE-ABS-KEY ("Warm Vertical Compaction") OR TITLE-ABS-KEY ("Vertical Compaction") OR TITLE-ABS-KEY ("Warm Vertical Condensation") OR TITLE-ABS-KEY ("Vertical Condensation") OR TITLE-ABS-KEY ("Thermoplasticized") OR TITLE-ABS-KEY ("Carrier-Based")) AND (TITLE-ABS-KEY ("Cold Lateral Compaction") OR TITLE-ABS-KEY ("Cold Lateral Condensation") OR TITLE-ABS-KEY ("Lateral Compaction") OR TITLE-ABS-KEY ("Lateral Condensation")) AND (TITLE-ABS-KEY (root AND canal AND filling) OR TITLE-ABS-KEY (gaps) OR TITLE-ABS-KEY (gap) OR TITLE-ABS-KEY (voids) OR TITLE-ABS-KEY (void) OR TITLE-ABS-KEY (empty AND spaces) OR TITLE-ABS-KEY (empty AND space) OR TITLE-ABS-KEY (quality)) AND (TITLE-ABS-KEY ("Microcomputed tomography") OR TITLE-ABS-KEY ("Micro-CT") OR TITLE-ABS-KEY ("MicroCT") OR TITLE-ABS-KEY ("CBCT") OR TITLE-ABS-KEY ("cone beam computed tomography"))	16
Web of Science	(((TS=("Warm Vertical Compaction" OR "Vertical Compaction" OR "Warm Vertical Condensation" OR "Vertical Condensation" OR "Thermoplasticized" OR "Carrier-Based")) AND TS=("Cold Lateral Compaction" OR "Cold Lateral Condensation" OR "Lateral Compaction" OR "Lateral Condensation")) AND TS=("Root Canal Filling" OR "Gap" OR "Voids" OR "Void" OR "Empty Spaces" OR "Empty Space" OR "Quality")) AND TS=("Microcomputed "Gaps" OR tomography" OR "Micro-CT" OR "MicroCT" OR "CBCT" OR "cone beam computed tomography")	18

suitable for laboratory studies but involves longer scanning times, smaller fields of view, and greater radiation exposure, which preclude clinical application. The different acquisition parameters of these imaging methods generate images with markedly different spatial resolutions. Micro-CT typically offers smaller voxel dimensions, more projections, and higher resolution than CBCT. This variation in resolution can influence the evaluation of obturation quality and must be considered when comparing findings derived from these modalities.

There have been many studies exploring the differences between the CLC and WVC obturation techniques, they evaluated these techniques using Micro-CT or CBCT images and compared the results (26–37). This systematic review and meta-analysis aims to compare CLC and WVC in root canal obturation quality, as evaluated by micro-CT and CBCT. By examining void volume, gutta-percha adaptation, and filling completeness, this review will determine which technique more reliably achieves optimal canal sealing. The results will lead future research to improve endodontic treatment outcomes and influence clinical decisions. The null hypothesis states that there is no discernible difference between CLC and WVC methods in terms of three-dimensional obturation quality.

MATERIALS AND METHODS

In accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (38), the processes of research article extraction, selection, and screening were integral to the meta-analysis conducted in this study. Table 1 provides a comprehensive summary of the specific search terms used, the databases accessed, and the duration of the search.

Research Strategy and Screening

We conducted a comprehensive evaluation of study articles using four databases—Web of Science, Embase, Scopus, and PubMed—focusing on publications available up to December 2024. The selection process adhered to PRISMA guidelines, ensuring a systematic approach for including research in the meta-analysis. Keywords for each database were meticulously chosen to support the analysis of articles across diverse disciplines, as outlined in Table 1. Titles and abstracts were independently reviewed by Z.Kh. and S.A., with M.D. acting as the third reviewer to resolve any disagreements. Only studies meeting the eligibility criteria and providing full-text availability were included.

The initial screening involved assessing titles and abstracts, followed by a thorough evaluation of the full texts to confirm eligibility. Clear inclusion and exclusion criteria were established. The PRISMA flow diagram (Fig. 1) (39) illustrates the selection process, detailing the number of studies screened, those assessed for eligibility, and the final studies included. Summaries of each included study were compiled, highlighting their characteristics, methodologies, and key findings (Appendix 1). Risk of bias in individual studies was assessed using standardized tools, providing context for interpreting the results (Appendix 2). Additionally, the methods for data extraction, synthesis, and the statistical approaches used in the meta-analysis were explained (Fig. 2).

Study Selection

Studies were eligible if they reported numerical outcomes for the percentage of gutta-percha filling within the entire canal length (referred to as "Complete Canal") or the apical third of the canal (referred to as "Apical Third") and used appropriate

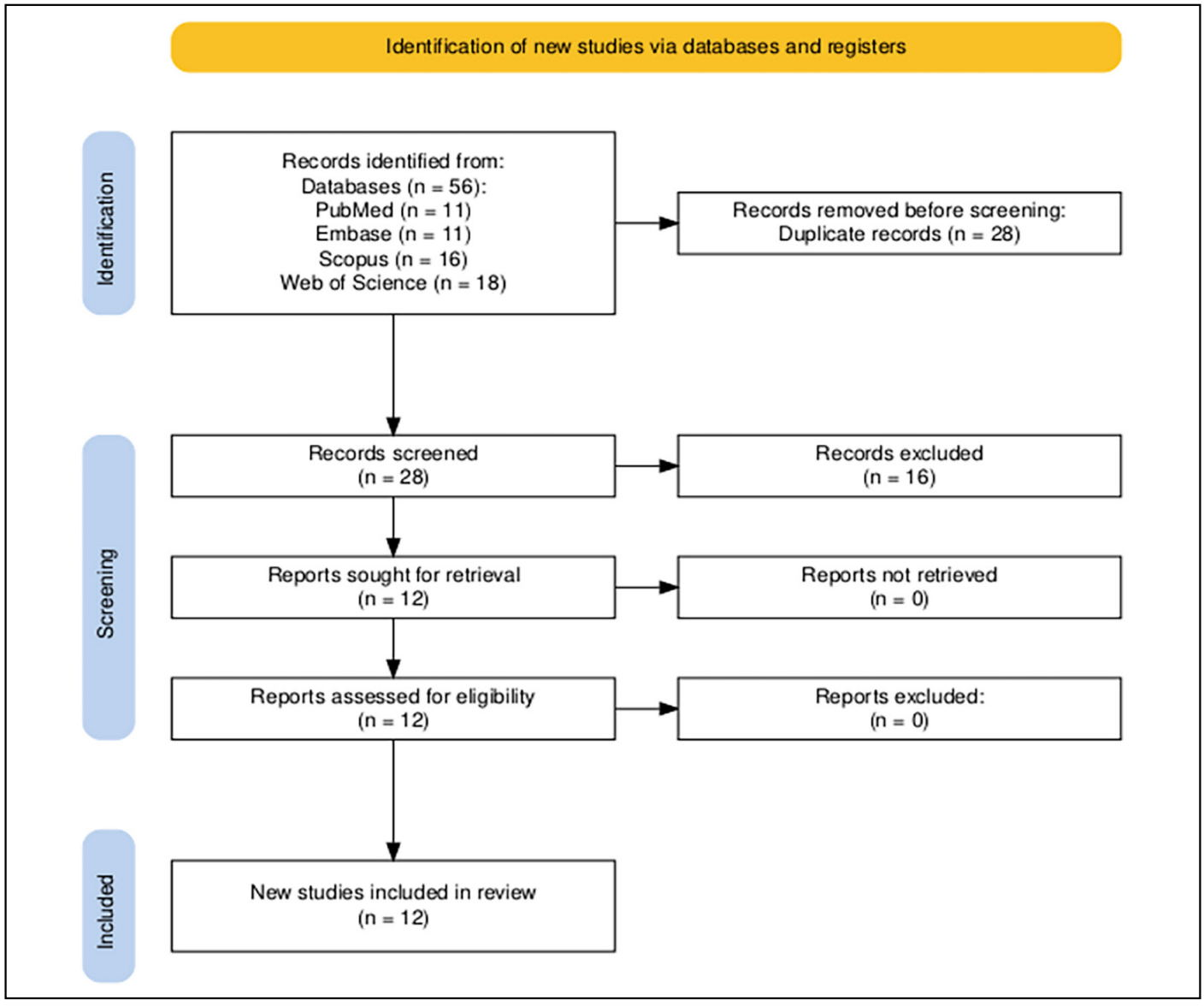

Figure 1. PRISMA flowchart.

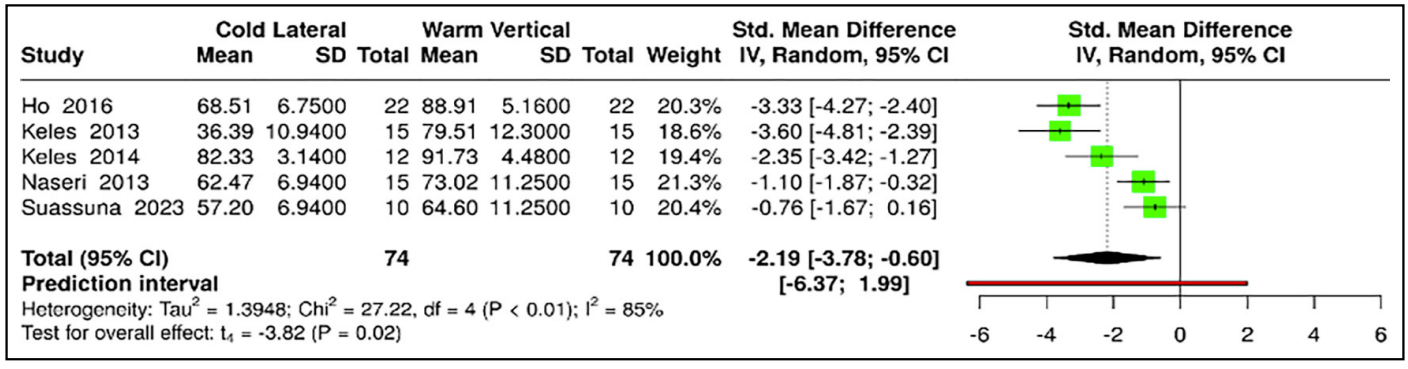

Figure 2. Random-effects meta-analysis of gutta-percha percentage in the complete canal length, showing SMDs with 95% confidence intervals.

SD: Standard deviation, Std: Standard, CI: Confidence interval, SMDs: Summary Measures and Data Synthesis.

preparation and obturation methods. Data extraction focused on study design, sample size, preparation and obturation techniques, evaluated parameters, and reported outcomes. Metrics such as void percentage and density were systematically extracted to ensure consistency. Due to inconsistent reporting across studies, outcome extraction prioritised gutta-percha volume as the most consistently reported quantitative parameter. We acknowledge this focus may favour WVC due to reduced sealer use inherent in this technique, and this limitation is discussed further.

Two included studies, Keles et al. (29) and Suassuna et al. (35), employed nonstandard experimental designs. Keles et al. (29) assessed obturation quality in artificially created internal resorption cavities, and Suassuna et al. (35) utilised thermomechanical compaction, a technique that differs from traditional WVC. We retained these studies due to their rigorous methodology, use of Micro-CT imaging, and relevance to warm obturation techniques. Their methodological differences are acknowledged as a potential source of heterogeneity and possible directional bias, which we address explicitly in the discussion.

The included studies provided data for both the Complete Canal and the Apical Third, with sample sizes ranging from 10 to 22 canals / single-rooted single canal teeth per group. While most studies reported complete data, two studies (Naseri 2013 and Suassuna 2023) lacked standard deviation (SD) values for certain outcomes.

PICO Question:

- Population (P): Extracted human teeth (or *in vitro* human root canals) prepared for endodontic treatment.
- Intervention (I): WVC techniques.
- Comparison (C): CLC techniques.
- Outcome (O): Three-dimensional obturation quality (measured by Micro-CT or CBCT) focusing on voids, gaps, and overall filling completeness.

The research question was "In human teeth (P), does WVC (I) compared to CLC (C) yield superior three-dimensional obturation quality (O), as assessed by Micro-CT or CBCT imaging?"

Eligibility Criteria

The following inclusion criteria were applied for the meta-analysis: 1) studies comparing two obturation techniques, WVC and CLC; 2) analyses conducted using either Micro-CT or CBCT images; 3) studies reporting findings and accuracy claims; and 4) publications available up to December 2024. Only studies meeting these criteria were included.

Exclusion criteria were as follows: 1) studies that performed a scoping review, systematic review, or meta-analysis; 2) those utilising other types of radiographic imaging; and 3) studies that did not directly compare WVC and CLC obturation techniques.

Quality Evaluation

The methodological quality of the included studies was evaluated using the CRIS (Checklist for Reporting *In-vitro* Studies) tool. All studies demonstrated high adherence to reporting standards, with clear descriptions of experimental design, sample size, and measurement protocols. Minor concerns were identified in some studies regarding the lack of reported randomisation and blinding procedures, specifically in Naseri 2013 and Suassuna 2023. Overall, the quality of the studies was deemed adequate for inclusion in the meta-analysis.

Handling Missing Data

The Cochrane Handbook (40) notes that when standard deviations are missing, they may be imputed using the mean of standard deviations from other studies in the meta-analysis. For studies missing SDs (Naseri 2013 and Suassuna 2023), values were imputed using the average SDs from other studies:

- Complete Canal: CLC SD=6.94, WVC SD=8.63
- Apical Third: CLC SD=11.25, WVC SD=15.38

This approach ensured consistency across analyses and enabled the inclusion of all studies. Sensitivity analyses were performed to assess the impact of these imputations on the pooled results.

Summary Measures and Data Synthesis

Given the notable heterogeneity found (I^2=80%, p<0.01), meta-analyses were performed using a random-effects model to account for any clinical and methodological variations among trials. To assess the effectiveness of the CLC and WVC approaches, mean differences and standardised mean differences (SMD) were computed with 95% confidence intervals (CIs).

Heterogeneity was assessed using I^2, τ^2, and Cochran's Q tests. Statistical analyses followed established meta-analysis frameworks.

RESULTS

Study Overview

A total of 12 studies were included in the systematic review, summarised in Appendix 1, with five studies contributing to the meta-analysis. The CLC cohort included 148 canals/single-rooted single canal teeth, while the WVC cohort included 148 canals/single-rooted single canal teeth. Group sizes ranged from 10 single-rooted single canal teeth to 22 canals per group. The meta-analysis, using a random-effects model with the inverse variance method, demonstrated a statistically significant difference between the two cohorts.

Heterogeneity and Robustness

Significant heterogeneity was observed (I^2=80%, p<0.01), suggesting variability in the magnitude or direction of the effect among studies. Sensitivity analyses, excluding studies with imputed SDs, showed no significant changes in results, confirming the robustness of the findings. Notably, Keles et al. (29) and Suassuna et al. (35) together contributed approximately 40% of the pooled sample. Given their methodological differences from other studies, they likely contributed to the observed high heterogeneity (I^2=80–85%).

Complete Canal

A meta-analysis was conducted to evaluate the obturation quality along the complete length of the canal, comparing CLC and WVC techniques using SMD in a random-effects model. Five studies were included, with a total of 74 samples in each group.

- The pooled SMD was -2.19 (95% CI: -3.78 to -0.60, p=0.02), indicating a statistically significant difference favouring the WVC technique for the complete length of the canal.
- The prediction interval was -6.37 to 1.99, suggesting considerable variability in the effect size if additional studies are conducted.
- Substantial heterogeneity was observed among the included studies (I^2=85%, Tau^2=1.3948, Chi^2=27.22, df=4, p<0.01), indicating significant variability in the study results.

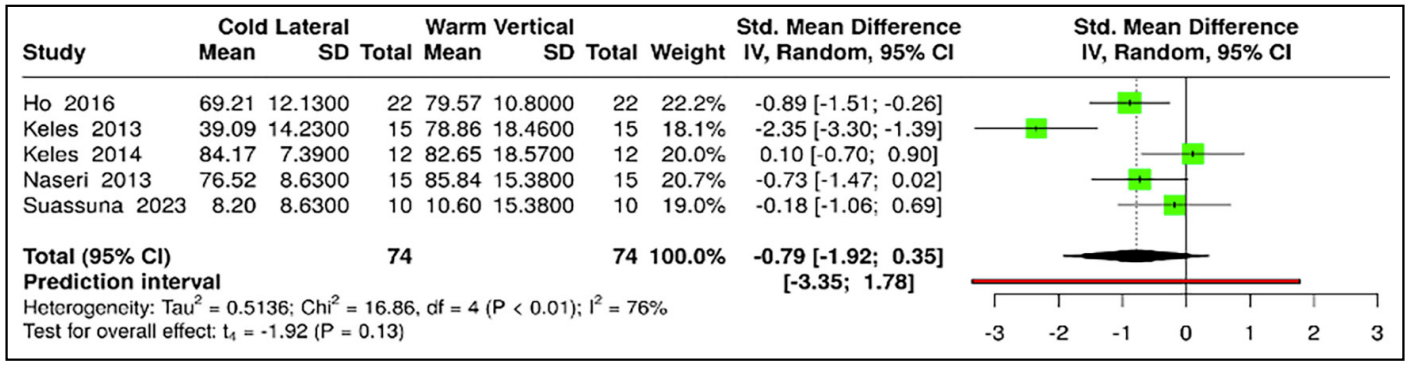

Figure 3. Random-effects meta-analysis of gutta-percha percentage in the apical third regions, showing SMDs with 95% confidence intervals.

SD: Standard deviation, Std: Standard, CI: Confidence interval, SMDs: Summary Measures and Data Synthesis.

While individual studies (28–30) showed a strong and statistically significant difference favouring the WVC technique, the high heterogeneity suggests that the observed effect may be influenced by differences in study populations, methodologies, or measurement protocols. Further research into standardized methods is recommended to confirm these findings (Fig. 2).

Apical Third

A meta-analysis was conducted to evaluate the obturation quality in the apical third of the canal, comparing CLC and WVC techniques based on SMD using a random-effects model. Five studies were included, with a total of 74 samples in each group.

- The pooled SMD was -0.79 (95% CI: -1.92 to 0.35, p=0.13), indicating a trend favouring the WVC technique for the apical third of the canal. However, the confidence interval crossed zero, indicating that the difference was not statistically significant.
- The prediction interval was -3.35 to 1.78, reflecting potential variability in the SMD if additional studies were included, further supporting the lack of definitive significance.
- Moderate heterogeneity was observed among the included studies (I^2=76%, Tau^2=0.5136, Chi^2=16.86, df=4, p<0.01).

While individual studies such as Ho (28), Keles (29, 30), and Naseri (33) demonstrated significant differences favouring the WVC technique in the apical third, the overall results were not statistically significant, and moderate heterogeneity was noted. These findings suggest the need for further high-quality studies to confirm the superiority of either technique for the apical third of the canal (Fig. 3).

Subgroup and Prediction Interval Analysis

Quality assessment

The quality assessment, detailed in Appendix 1, demonstrated high methodological standards across all included studies. Most studies scored ≥26 out of 34 on the CRIS checklist. Common strengths included comprehensive descriptions of sample size, interventions, and statistical methods. Minor concerns, particularly the absence of randomisation and blinding in studies such as Naseri 2013 and Suassuna 2023, were unlikely to significantly influence the outcomes.

DISCUSSION

This systematic review and meta-analysis compared the efficacy of CLC and WVC techniques in endodontic obturation, evaluated using advanced imaging modalities such as Micro-CT and CBCT. By synthesising data from multiple studies, this work provides a comprehensive understanding of the relative strengths and limitations of these widely utilised obturation techniques. The analysis underscores important differences in the obturation quality, void presence, and adaptation to the root canal walls achieved by each method, as well as critical methodological and clinical implications. The high heterogeneity observed in our meta-analysis (I^2=80–85%) underscores the variability in included studies and limits the certainty of the pooled estimates, warranting cautious interpretation. The inclusion of studies with non-standard methodologies, Keles et al. (29) examining internal resorptive cavities and Suassuna et al. (35) evaluating thermomechanical compaction, represents a notable limitation. While these studies provided valuable data on obturation quality using 3D imaging, their protocols differ from conventional root canal treatment scenarios. Their inclusion may have skewed the pooled results in favour of WVC. Therefore, our conclusions are presented as descriptive and should be interpreted with caution.

The results of the meta-analysis showed a statistically significant difference favouring WVC over CLC for the complete canal length, with a pooled SMD of -2.19 (95% CI: -3.78 to -0.60, p=0.02). This finding highlights the ability of WVC to achieve better three-dimensional filling completeness and adapt to the complex geometry of the root canal system.

The superior performance of WVC is likely attributable to the thermoplasticised gutta-percha's ability to flow and conform closely to the canal walls, filling irregularities and minimising voids. Studies such as Ho (28) and Keles (29, 30) strongly support this observation, reporting denser fillings and significantly lower void percentages with WVC compared to CLC. Moreover, the findings align with the theoretical advantages of WVC described in previous literature, which emphasise enhanced sealing ability and reduced microleakage when thermoplasticised gutta-percha is used.

In contrast, CLC relies on the frictional fit of accessory cones and sealer to achieve obturation, which often leads to the presence of voids and incomplete canal wall adaptation. While CLC remains a staple in endodontic education and practice due to

its cost-effectiveness and relative ease of use, the findings suggest that its efficacy may be limited in achieving the ideal three-dimensional seal, particularly in complex canal anatomies.

Despite these differences, it is important to note the substantial heterogeneity among the included studies (I^2=85%). The observed variability may be attributed to differences in study design and methodology. Factors such as sample preparation techniques, imaging resolution, and evaluation criteria varied across studies. For example, studies utilising high-resolution Micro-CT scanners, such as those by Keles (29, 30) and Li (32), may report more precise measurements of voids and gutta-percha adaptation compared to those relying on lower-resolution CBCT scans. Although most included studies adhered to reporting guidelines, several lacked explicit details on randomization and blinding procedures, which may introduce bias even in *in vitro* designs and should be addressed in future research. Standardising these parameters in future research is essential to strengthen the evidence base and provide clearer guidance for clinical practice.

The results for the apical third of the canal presented a more nuanced picture. While a trend favouring WVC was observed (pooled SMD=-0.79), the confidence interval crossing zero (95% CI: -1.92 to 0.35, p=0.13) indicates a lack of statistical significance. This finding reflects the challenges associated with achieving complete obturation in the apical region, where anatomical complexity and limited access can hinder the performance of any technique. The inconclusive findings regarding the apical third highlight a limitation of the evidence and suggest that neither technique can be considered definitively superior in this critical region.

Studies such as Keles (29, 30) and Naseri (33) reported notable advantages of WVC in the apical third, citing fewer voids and better adaptation. However, other studies, including Zand (36), found no significant differences between the two techniques in this region. This variability may be due to differences in the canal preparation techniques, the type of sealer used, or the modality employed imaging. The moderate heterogeneity observed (I^2=76%) further emphasises the need for standardised methodologies and well-controlled experimental designs.

Interestingly, while WVC's thermoplasticised approach offers theoretical advantages in the apical third, its reliance on precise operator technique and control of heating parameters introduces a potential source of variability. The results suggest that while WVC may be more effective in experienced hands, its benefits over CLC in the apical region are less consistent. This underscores the importance of operator training and technique standardisation to maximise the efficacy of WVC. Operators experience likely influences WVC performance more than CLC due to the technical demands of thermoplasticised obturation, which should be further investigated.

The use of advanced imaging modalities was a key strength of this review, enabling detailed assessments of obturation quality. Micro-CT's high resolution allows for precise volumetric analysis and identification of voids. Several studies, including those by Keles (29, 30) and Ho (28), utilised Micro-CT to provide granular insights into void distribution and gutta-percha adaptation.

CBCT, on the other hand, offers a more practical alternative for clinical settings due to its lower cost and ease of use. While its resolution is inferior to Micro-CT, CBCT remains valuable for evaluating gross obturation quality and is widely accessible in clinical practice. The complementary strengths of these modalities enhance the robustness of the findings, but their inherent limitations—such as radiation exposure and cost for Micro-CT—should be acknowledged. Future research could explore hybrid approaches that integrate the strengths of both modalities to provide a more comprehensive assessment.

However, the choice between CLC and WVC should be guided by patient-specific factors, including canal morphology, infection severity, and economic considerations. For example, in cases involving simple, straight canals, CLC may provide satisfactory results while minimizing treatment costs. Conversely, in complex or anatomically challenging cases, the superior performance of WVC may justify its higher cost and complexity.

The high heterogeneity observed in this review highlights several methodological limitations in the included studies. Variability in sample preparation, obturation protocols, and evaluation criteria likely contributed to the observed differences in outcomes. Additionally, the imputation of missing standard deviations, while necessary for comprehensive analysis, may introduce bias, as seen in studies such as Naseri (2013) and Suassuna (2023). Sensitivity analyses, which showed no significant impact of these imputations on the overall results, mitigate this concern but emphasise the need for more robust reporting in primary studies. As obturation quality represents a surrogate outcome, and no difference in clinical success between CLC and WVC has been consistently demonstrated in long-term studies, these findings should not be interpreted as evidence of clinical superiority.

It is noteworthy that studies by Ng et al. (41) and Peng et al. (42) report no significant difference in long-term clinical outcomes between cold lateral condensation and warm gutta-percha obturation techniques, despite differences in 3D filling quality observed in laboratory studies. Li et al.'s (32) meta-analysis of 10 clinical trials found no significant differences in post-operative pain, long-term success, or overall obturation quality between the two techniques, although warm GP showed a higher rate of overextension

This study has several important limitations. First, two studies (29, 35) were methodologically divergent from the others. Keles et al. (29) examined internal resorption cavities rather than full canal obturation, and Suassuna et al. (35) employed thermomechanical compaction rather than conventional WVC. While both studies offered valuable 3D imaging data, their inclusion may overrepresent WVC's performance and this may limit the generalizability of our findings to routine clinical settings. These factors likely contributed to the substantial heterogeneity observed and should be considered when interpreting the results.

A key limitation of this review is the inclusion of studies employing two different imaging modalities, Micro-CT and CBCT, which differ significantly in resolution and image quality. This methodological heterogeneity likely influenced the evaluation of obturation quality and introduces additional variability

into the meta-analysis. Despite use of a random-effects model, the magnitude of heterogeneity (I^2=80-85%) substantially reduces confidence in pooled estimates. This limitation is compounded by methodological differences and reinforces the need for cautious interpretation.

Another limitation of this study was that the primary outcome measure was gutta-percha volume, rather than total obturation quality (including sealer and voids), which may selectively favour WVC due to its material characteristics.

Future research should aim to standardize methodologies by developing uniform protocols for canal preparation, obturation, and evaluation, thereby minimising variability and enhancing comparability across studies. They should adopt standardized protocols for sample preparation, obturation techniques, imaging parameters, and outcome reporting. Methodological standardization will help reduce variability and improve comparability among studies. It is also important to assess the long-term clinical success of CLC and WVC over extended follow-up periods to better understand their impact on patient outcomes. Additionally, investigations into advanced imaging techniques, such as hybrid imaging approaches and novel technologies, could improve the accuracy and clinical relevance of obturation quality assessments. Finally, examining how operator experience and training affect the performance of obturation techniques, especially WVC, will help identify areas for improvement and training needs.

CONCLUSION

This meta-analysis found that WVC appears to achieve a higher gutta-percha volume along the full canal length under experimental conditions. However, high heterogeneity, methodological variability, and lack of clinical outcome data limit the applicability of these findings to clinical practice. This analysis describes differences in 3D filling quality between obturation techniques under experimental conditions; however, significant heterogeneity and the surrogate nature of these outcomes preclude direct clinical recommendations. Therefore, conclusions drawn from this analysis must be interpreted with caution due to significant heterogeneity among included studies.

Disclosures

Online Appendix Files: https://jag.journalagent.com/eurendodj/abs_files/EEJ-22599/EEJ-22599_(0)_Appendices.pdf

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REFERENCES

1. Schilder H. Filling root canals in three dimensions. 1967. J Endod 2006; 32:281–90. [Crossref]
2. Chokkalingam M, Ramaprabha, Kandaswamy D. Three-dimensional helical computed tomographic evaluation of three obturation techniques: *In vitro* study. J Conserv Dent 2011; 14(3):273–6. [Crossref]
3. Cailleteau JG, Mullaney TP. Prevalence of teaching apical patency and various instrumentation and obturation techniques in United States dental schools. J Endod 1997; 23(6):394–6. [Crossref]
4. Levitan ME, Himel VT, Luckey JB. The Effect of Insertion Rates on Fill Length and Adaptation of a Thermoplasticized Gutta-Percha Technique. J Endod 2003; 29:505–8. [Crossref]
5. Leduc J, Fishelberg G. Endodontic Obturation: A Review. Gen Dent 2003; 51:232–3.
6. Cueva-Goig R., Forner-Navarro L., Llena-Puy M.C. Microscopic Assessment of the Sealing Ability of Three Endodontic Filling Techniques. J Clin Exp Dent 2016; 8:e27–e31. [Crossref]
7. Budd C.S., Weller R.N., Kulild J.C. A Comparison of Thermoplasticized Injectable Gutta-Percha Obturation Techniques. J Endod 1991; 17:260–4. [Crossref]
8. Moccia E, Carpegna G, DellAcqua A, Alovisi M, Comba Allegra, Berrutti E. Evaluation of the root canal tridimensional filling with warm vertical condensation, carrier-based technique and single cone with bioceramic sealer: a micro-CT study. G Ital Endod 2020; 34:55–62.
9. Hadis M, Camilleri J. Characterization of heat resistant hydraulic sealer for warm vertical obturation. Dent Mater 2020; 36(9):1183–9. [Crossref]
10. Canakci BC, Sungur R, Er O. Comparison of warm vertical compaction and cold lateral condensation of α, β gutta-percha and resilon on apically extruded debris during retreatment. Niger J Clin Pract 2019; 22(7):926–31. [Crossref]
11. Donnermeyer D, Urban K, Bürklein S, Schäfer E. Physico-chemical investigation of endodontic sealers exposed to simulated intracanal heat application: epoxy resins and zinc oxide-eugenols. Int Endod J 2020; 53(5):690–7. [Crossref]
12. Hawi N, Pedullà E, La Rosa GRM, Conte G, Nehme W, Neelakantan P. Influence of Coronal Flaring on the Shaping Ability of Two Heat-Treated Nickel-Titanium Endodontic Files: A Micro-Computed Tomographic Study. J Clin Med 2023; 12(1):357. [Crossref]
13. Medeiros TC, Lima CO, Barbosa AFA, Augusto CM, Bruno AMV, Lopes RT, Amoroso-Silva PA, Marceliano-Alves MF. Shaping ability of reciprocating and rotary systems in oval-shaped root canals: a microcomputed tomography study. Acta Odontol Latinoam. 2021; 34(3):282–8. [Crossref]
14. Moore J, Fitz-Walter P, Parashos P. A micro-computed tomographic evaluation of apical root canal preparation using three instrumentation techniques. Int Endod J. 2009; 42(12):1057–64. [Crossref]
15. Dufresne T, Chmielewski P, Borah B, Laib A. Microcomputed tomography and its applications. In: Gary E. Wnek, Gary L. Bowlin, editors. Encyclopaedia of Biomaterials and Biomedical Engineering. 2nd ed. New York: Informa healthcare; 2004. pp. 94–1003.
16. Marciano MA, Duarte MAH, Ordinola-Zapata R, Del Carpio-Perochena A, Cavenago BC, Villas Bôas MH, et al. Applications of micro-computed tomography in endodontic research. Curr Microsc Contrib Adv Sci Technol 2012; 2:782–788.
17. Saber S.E.D.M., El Sadat S.M.A. Effect of Altering the Reciprocation Range on the Fatigue Life and the Shaping Ability of WaveOne Nickel-Titanium Instruments. J Endod 2013; 39:685–688. [Crossref]
18. Patel S, Kanagasingam S, Mannocci F. Cone beam computed tomography (CBCT) in endodontics. Dent Update 2010; 37(6):373–9. [Crossref]
19. Al-Manei KK, Al-Hadlaq SM. Evaluation of the root canal shaping ability of two rotary nickel-titanium systems. Int Endod J 2014; 47(10):974–9. [Crossref]
20. 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(2):1788–91. [Crossref]
21. Cohenca N., Shemesh H. Clinical applications of cone beam computed tomography in endodontics: A comprehensive review. Quintessence Int 2015; 46(6):465–80.
22. Pérez Morales MLN, González Sánchez JA, Olivieri JG, Elmsmari F, Salmon P, Jaramillo DE, Terol FD. Micro-computed Tomographic Assessment and

Comparative Study of the Shaping Ability of 6 Nickel-Titanium Files: An *In Vitro* Study. J Endod 2021; 47(5):812–9. [Crossref]
23. Hartmann MS, Barletta FB, Camargo Fontanella VR, Vanni JR. Canal transportation after root canal instrumentation: a comparative study with computed tomography. J Endod 2007; 33(8):962–5. [Crossref]
24. Dhingra A, Banerjee S, Yadav V, Aggarwal N. Canal Shaping with ProTaper Next and ProTaper Universal: A Comparative Study. Ann Dent Res 2014; 4:6–14.
25. Elemam RF, Azul AM, Dias J, El Sahli K, de Toledo Leonardo R. *In Vitro* Research Methods Used to Evaluate Shaping Ability of Rotary Endodontic Files-A Literature Review. Dent J (Basel) 2024; 12(10):334. [Crossref]
26. Abdo SB, Darrat AA, Masudi SM, Luddin N, Husien A. Sealing ability of gutta-percha/nano HA versus resilon/epiphany after 20 months using an electrochemical model - an *in vitro* study. Braz J Oral Sci 2012; 11(3):387–91.
27. Gupta G, Singla M, Kaur H, Mittal L, Gupta S, Kaur S. Comparative evaluation of the quality and homogeneity of different obturating systems using cone-beam computed tomography - An *in vitro* study. J Conserv Dent Endod 2023; 26(4):414–9.
28. Ho ES, Chang JW, Cheung GS. Quality of root canal fillings using three gutta-percha obturation techniques. Restor Dent Endod 2016; 41(1):22–8. [Crossref]
29. Keles A, Ahmetoglu F, Uzun I. Quality of different gutta-percha techniques when filling experimental internal resorptive cavities: a micro-computed tomography study. Aust Endod J 2014; 40(3):131–5. [Crossref]
30. Keleş A, Alcin H, Kamalak A, Versiani MA. Micro-CT evaluation of root filling quality in oval-shaped canals. Int Endod J 2014; 47(12):1177–84. [Crossref]
31. Kim J, Vo K, Dhaliwal GS, Takase A, Primus C, Komabayashi T. Micro-CT determination of the porosity of two tricalcium silicate sealers applied using three obturation techniques. J Oral Sci 2024; 66(3):163–8. [Crossref]
32. Li GH, Niu LN, Selem LC, Eid AA, Bergeron BE, Chen JH, et al. Quality of obturation achieved by an endodontic core-carrier system with crosslinked gutta-percha carrier in single-rooted canals. J Dent 2014; 42(9):1124–34. [Crossref]
33. Naseri M, Kangarlou A, Khavid A, Goodini M. Evaluation of the quality of four root canal obturation techniques using micro-computed tomography. Iran Endod J 2013; 8(3):89–93.
34. Selem LC, Li GH, Niu LN, Bergeron BE, Bortoluzzi EA, Chen JH, et al. Quality of obturation achieved by a non-gutta-percha-based root filling system in single-rooted canals. J Endod 2014; 40(12):2003–8. [Crossref]
35. Suassuna FCM, de Araujo DKM, Amorim AMAM, Melo SLS, Heck RJ, Antonino ACD, et al. Thermal and volumetric assessment of endodontic filling techniques using infrared thermography and micro-CT. J Oral Sci 2023; 65(1):34–9. [Crossref]
36. Zand V, Milani AS, Tehranchi P, Sabzevar SB, Godarzi O. Comparative CBCT Assessment of Obturation Quality in Different Obturation Techniques. J Dent Mater Tech 2022; 11(2):84–92.
37. Zongova-Adem SE, Tsenova-Ilieva IK, Dogandzhiyska VD, Topalova-Pirinska SZ, Karova EG. ProTaper universal retreatment retreatment potential in oval-shaped canals filled with different obturation techniques-A micro-computed tomography study. J Intl Soc Prev Community Dent 2024; 14(2):152–60. [Crossref]
38. Moher D, Liberati A, Tetzlaff J, Altman DG; PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 2009; 6(7):e1000097. [Crossref]
39. Haddaway NR, Page MJ, Pritchard CC, McGuinness L.A. PRISMA2020: PRISMA2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis. Campbell Syst Rev 2022; 18(2):e1230. [Crossref]
40. Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, et al, editor(s). Cochrane Handbook for Systematic Reviews of Interventions. 2nd Edition. Chichester (UK): John Wiley & Sons, 2019. [Crossref]
41. Ng YL, Mann V, Rahbaran S, Lewsey J, Gulabivala K. Outcome of primary root canal treatment: systematic review of the literature - part 1. Effects of study characteristics on probability of success. Int Endod J 2007; 40(12):921–39. [Crossref]
42. Peng L, Ye L, Tan H, Zhou X. Outcome of root canal obturation by warm gutta-percha versus cold lateral condensation: a meta-analysis. J Endod 2007; 33(2):106–9. [Crossref]