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Root Canal Obturation Quality in 3D-Printed C-Shaped Canals with Different Filling Techniques

Kvaliteta opturacije korijenskog kanala u 3D printanim kanalima u obliku slova C s različitim tehnikama punjenja

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Abstract

Objectives: This study aimed to assess the quality of canal obturation in 3D-printed C-shaped canals using Micro-CT and dye penetration with different filling techniques. **Methodology:** Sixty 3D-printed teeth with C-shaped canals were obturated using: AH Plus with continuous wave (AHCW), iRoot SP with single cone (SPSC) and iRoot SP with continuous wave (SPCW). Micro-CT was used for 3D reconstruction in two regions: 0~8 mm (overall canal) and 0~3 mm (apical segment). The volume of voids (V1) and total canal volume (V) were used to calculate porosity as (V1/V) × 100%. Sealing quality was assessed by dye penetration. **Results:** Results showed that AHCW exhibited significantly lower porosity within 8 mm (5.17%) compared to SPSC (9.02%) and SPCW (8.55%), (P < 05). No significant porosity differences were observed within 3 mm or in dye penetration. **Conclusion:** AHCW achieved better obturation in the middle and upper segments, with no significant differences among techniques in the apical segment.

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Introduction

Achieving a three-dimensional, hermetic seal of the root canal system is a pivotal step in endodontic treatment, as it prevents bacterial re-infiltration and subsequent treatment failures (1). However, the intrinsic complexity of root canal morphology, which is exemplified by C-shaped root canals, often complicates the objective of endodontic treatment. The C-shaped root canal, more commonly found in the mandibular second molar, can also occur in other molars, with its incidence particularly high in the East Asian population, reaching as high as 39.6% (2, 3). Their defining characteristic is a continuous, ribbon-like canal configuration composed of

Uvod

Postizanje trodimenzionalnoga, hermetičkog brtvljenja korijenskog kanala ključno je u endodontskom liječenju jer sprječava ponovnu infiltraciju bakterija i naknadne neuspjehe u liječenju (1). Ali intrinzična složenost morfologije korijenskog kanala, koja se ogleda u korijenskim kanalima u obliku slova C, često komplicira endodontsko liječenje. Korijenski kanal u obliku slova C, koji se češće nalazi u mandibularnome drugom kutnjaku, može se pojaviti i u drugim kutnjacima s incidencijom posebno visokom u istočnoazijskoj populaciji – doseže čak 39,6 % (2, 3). Njihova definirajuća karakteristika je kontinuirana – vrpčasta konfiguracija kanaone or more interconnected canals and fin-like structures, thus creating considerable difficulty in mechanical cleaning and chemical disinfection(4). These intricate anatomies commonly harbor residual debris and microorganisms, making long-term sealing challenging and increasing the likelihood of failure. Indeed, studies have found that the most prevalent reasons for unsuccessful outcomes in C-shaped canal treatments include poorly sealed canals (45.2%), persistent isthmuses (23.8%), unlocated canals, and overfilling(5).

Given these complexities, identifying the most effective obturation technique for C-shaped canals is of paramount importance. The anatomical irregularities of C-shaped canals make it challenging to achieve homogenous and void-free obturation, further complicating clinical decision-making. Previous research has yielded inconsistent findings, particularly regarding obturation quality and the degree of canal filling porosity (6-8). To resolve the conflicting results reported in previous studies and to overcome the inconsistency of natural C-shaped canal morphology, our study employed 3D-printed resin teeth to standardize the initial morphology and mitigate the inconsistency inherent in human teeth samples. By using this approach, we have ensured reproducibility and minimized anatomical variability, which often compromises the reliability of comparative studies. We compared the obturation quality of three distinct protocols in C-shaped canals: AH Plus sealer combined with the continuous wave technique (AHCW), iRoot SP sealer combined with a single-cone technique (SPSC), and iRoot SP sealer combined with continuous wave obturation (SPCW). AH Plus, a resin-based sealer, has been extensively studied for its favorable chemical and biological properties (9, 10). Conversely, iRoot SP is a bioceramic sealer known for its optimal flowability, biocompatibility, and potentially for enhancing apical sealing and osteogenic differentiation (11). These attributes make it a promising alternative to conventional sealers. Combined with the time-saving continuous wave and single-cone techniques, which have gained popularity in clinical practice (12), these protocols warrant a thorough comparative evaluation to determine their effectiveness in addressing the complexities of C-shaped canals.

To strengthen the robustness of our findings, we employed both micro-computed tomography (Micro-CT) and dye penetration tests. Micro-CT provides detailed three-dimensional imaging, facilitating the detection and quantification of obturation porosities, while allowing non-destructive evaluation of the internal structure of the root canal filling (13). However, it can be susceptible to artifacts (14) and may not directly reflect the sealing ability of the obturated canal. Therefore, the dye penetration test serves as a complementary tool, offering a direct assessment of the seal quality. By integrating these methods, our study aimed to provide comprehensive insights into the obturation efficacy of different sealers and techniques in C-shaped canal anatomies. The null hypothesis of this study was that there are no differences among the various filling materials and methods in terms of filling quality (including porosity and dye penetration).

la sastavljena od jednoga ili više uzajamno povezanih kanala i struktura nalik na peraje, što stvara znatne poteškoće u mehaničkom čišćenju i kemijskoj dezinfekciji (4). Te složene anatomije obično sadržavaju ostatke ostataka i mikroorganizama, što dugoročno brtvljenje čini izazovnim i povećava mogućnost neuspjeha. Doista, autori studija otkrili su da su najčešći razlozi za neuspjeh ishoda u liječenju kanala u obliku slova C loše zatvoreni kanali (45,2 %), perzistentni istmusi (23,8 %), nelocirani kanali i prepunjenost (5).

S obzirom na tu složenost, najvažnije je identificirati najučinkovitiju tehniku opturacije kanala u obliku slova C. Anatomske nepravilnosti takva kanala otežavaju postizanje homogene opturacije bez šupljina, što dodatno komplicira kliničko donošenje odluka. U dosadašnjim istraživanjima nedosljedni su nalazi, posebno kad je riječ o kvaliteti opturacije i stupnju poroznosti punjenja kanala (6 – 8). Da bismo riješili oprečne rezultate prijavljene u dosadašnjim studijama i prevladali nedosljednost prirodne morfologije kanala u obliku slova C, u našoj studiji koristili smo se 3D printanim zubima od smole kako bismo standardizirali početnu morfologiju i ublažili nedosljednost svojstvenu uzorcima ljudskih zuba. Korištenjem toga pristupa osigurali smo ponovljivost i minimizirali anatomsku varijabilnost, što često ugrožava pouzdanost komparativnih studija. Usporedili smo kvalitetu opturacije trima različitim protokolima u kanalima u obliku slova C: AH Plus brtvilo u kombinaciji s tehnikom kontinuiranoga vala (AHCW), iRoot SP brtvilo u kombinaciji s tehnikom jednoga konusa (SPSC) i iRoot SP brtvilo u kombinaciji s opturacijom kontinuiranoga vala (SPCW). AH Plus, brtvilo na bazi smole detaljno je proučavan zbog povoljnih kemijskih i bioloških svojstava (9, 10). Suprotno tomu, iRoot SP biokeramičko je brtvilo poznato po optimalnoj protočnosti, biokompatibilnosti i potencijalu za poboljšanje apikalnog brtvljenja i osteogene diferencijacije (11). Ta svojstva čine ga obećavajućom alternativom za konvencionalne brtvila. U kombinaciji s tehnikama kontinuiranoga vala i jednoga konusa koje štede vrijeme, a stekli su popularnost u kliničkoj praksi (12), ti protokoli zahtijevaju temeljitu komparativnu evaluaciju kako bi se ustanovila njihova učinkovitost u rješavanju složenosti kanala u obliku slova C.

Kako bismo ojačali robusnost naših nalaza, koristili smo se mikrokompjutoriziranom tomografijom (Mikro-CT) i testovima penetracije boje. Mikro-CT detaljno trodimenzionalno snima i olakšava otkrivanje i kvantifikaciju poroznosti punjenja, a istodobno omogućuje nerazornu procjenu unutarnje strukture ispuna korijenskog kanala (13). No može biti osjetljiv na artefakte (14) i ne mora izravno odražavati svojstvo brtvljenja punjenog kanala. Zato test penetracije boje, nudeći izravnu procjenu kvalitete brtvljenja, služi kao komplementarni alat. Integracijom tih metoda, odredili smo kao naš cilj pružiti sveobuhvatni uvid u učinkovitost opturacije različitih punila i tehnika u anatomijama kanala u obliku slova C. Nulta hipoteza naše studije bila je da nema razlika među različitim materijalima i metodama punjenja kad je riječ o kvaliteti punjenja (uključujući poroznost i penetraciju boje).

Materials and Methods

Selection of samples

A total of 60 uniform, transparent 3D-printed resin teeth were included in the study (Xingxing Medical Equipment Co., Ltd., China). Commercially available 3D-printed resin teeth featuring a C2 configuration in the middle and upper segments and a C3 configuration in the apical segment were selected (Figure. 1).

Sample size calculation

Sample size calculation was performed using G*Power 3.1.9.7 (Universitat Kiel, Kiel, Germany). Based on results from our preliminary pilot test, the estimated minimum sample size was 45 (effect size: 0.6, alpha error: 0.05, power: 95%). With an allocation ratio of 1:1, a minimum of 16 samples per group was considered appropriate. To account for potential sample loss during the experiment, the final sample size for this study was set at 20 per group.

Root canal preparation

Prior to instrumentation, a size 10 K-file (Dentsply Maillefer, Ballaiques, Switzerland) was passively inserted into the canals until its tip was visible at the apical foramen. The working length (WL) was then determined to be 1 mm shorter than the measurements obtained at the foraminal opening. #10 and #15 K-files were used before the use of rotary instruments to establish a safe glide path. Subsequently, ProTaper Next file (X1-X3) (Dentsply Sirona, USA) was used with X-Smart Plus endodontic motor at 300 rpm and 2.0 Ncm torque until the working length was reached. During the procedure, irrigation with 1% sodium hypochlorite was performed between each file insertion. Finally, irrigation was performed using the EndoActivator System (Dentsply Tulsa Dental Specialties, Tulsa, OK, USA). The canals were filled with 1% sodium hypochlorite, and activation was carried out with a 22 mm, medium size polymer tip for a total of 1 minute for each canal, consisting of three cycles of 20 seconds each, with irrigation and activation alternated. The 30#/.06 cone was confirmed to match the prepared root canal. The schematic diagram after root canal preparation is shown in Figure 2**.**

Root canal filling

The prepared samples were randomly divided into 3 groups with 20 teeth in each group.

Group A: AH plus by continuous wave obturation technique (AHCW)

The C-shaped root canals were filled with 3 pieces of 30#/.06 tapered gutta-percha cones (Dentsply, Tianjin, China) with AH plus (Dentsply DeTrey, Konstanz, Germany). The pre-fitted master gutta-percha point was coated with a thin layer of sealer and gently inserted into the root canal to ensure coverage of the walls. It was then recoated with sealer and slowly inserted into the root canal to the full WL. A B&L-alpha heat-carrier tip (B&L, *Biotech Inc* Korea) was

Materijali i metode

Odabir uzoraka

U studiju je bilo uključeno ukupno 60 ujednačenih, prozirnih 3D printanih zuba od smole (Xingxing Medical Equipment Co., Ltd., Kina). Odabrani su takvi komercijalno dostupni zubi s C2 konfiguracijom u srednjem i gornjem segmentu te C3 konfiguracijom u apikalnom segmentu (slika 1.).

Izračun veličine uzorka

Izračun veličine uzorka obavljen je u programu G*Power 3.1.9.7 (Sveučilište u Kielu, Njemačka). Na temelju rezultata našega preliminarnog pilot-testa, procijenjena minimalna veličina uzorka bila je 45 (veličina učinka: 0,6, alfa pogreška: 0,05, snaga: 95 %). Uz omjer raspodjele od 1 : 1, smatralo se prikladnim minimalno 16 uzoraka u skupini. Kako bi se uzeo u obzir potencijalni gubitak uzoraka tijekom eksperimenta, konačna veličina uzorka za ovu studiju postavljena je na 20 u skupini.

Priprema korijenskog kanala

Prije instrumentacije, K-turpija veličine 10 (Dentsply Maillefer, Ballaiques, Švicarska) pasivno je umetnuta u kanale dok joj vrh nije bio vidljiv na apikalnom foramenu. Radna duljina (WL) zatim je određena kao 1 mm kraća od mjerenja dobivenih na foraminalnom otvoru. K-turpije veličine 10 i 15 korištene su prije upotrebe rotacijskih instrumenata da bi se uspostavio siguran klizni put. Nakon toga upotrijebljena je turpija ProTaper Next (X1-X3) (Dentsply Sirona, SAD) s endodontskim motorom X-Smart Plus pri 300 okretaja u minuti i okretnim momentom od 2,0 Ncm dok se nije dosegnula radna duljina. Tijekom postupka, između svakog umetanja turpije, obavljeno je ispiranje 1-postotnim natrijevim hipokloritom. Na kraju, ispiranje je obavljeno s pomoću sustava EndoActivator (Dentsply Tulsa Dental Specialties, Tulsa, OK, SAD). Kanali su ispunjeni 1-postotnim natrijevim hipokloritom, a aktivacija je provedena polimernim vrhom srednje veličine od 22 mm u ukupnom trajanju od 1 minute za svaki kanal, što se sastojalo od triju ciklusa od 20 sekunda, s naizmjeničnim ispiranjem i aktivacijom. Potvrđeno je da konus od 30#/.06 odgovara pripremljenom korijenskom kanalu. Shematski dijagram nakon pripreme korijenskog kanala vidi na slici 2.

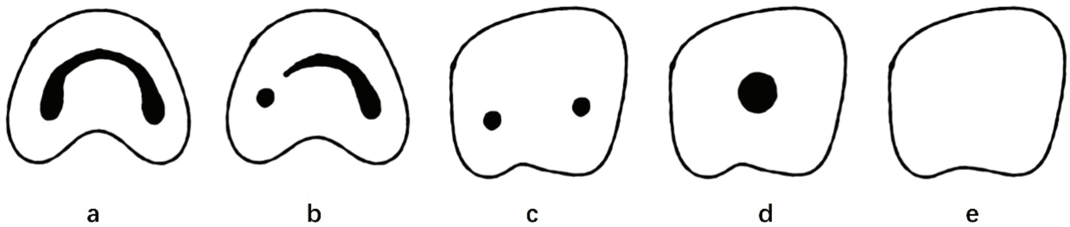
Punjenje korijenskog kanala

Pripremljeni uzorci nasumično su podijeljeni u tri skupine s 20 zuba u svakoj.

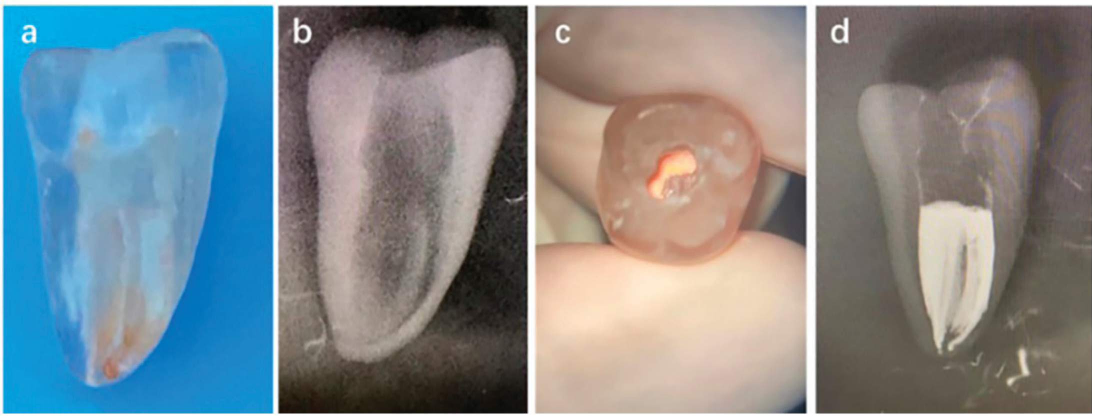
Skupina A: AH plus tehnikom kontinuiranoga vala (AHCW)

Korijenski kanali u obliku slova C ispunjeni su trima komadima gutaperki konusa od 30#/.06 (Dentsply, Tianjin, Kina) s AH plusom (Dentsply DeTrey, Konstanz, Njemačka). Prije toga je postavljeni glavni gutaperkin konus premazan tankim slojem brtvila i nježno umetnut u korijenski kanal kako bi se osiguralo prekrivanje stijenki. Zatim je ponovno premazan brtvilom i polako umetnut u korijenski kanal do pune širine korijena (WL). U kanal je uveden vrh no-

1.



2.



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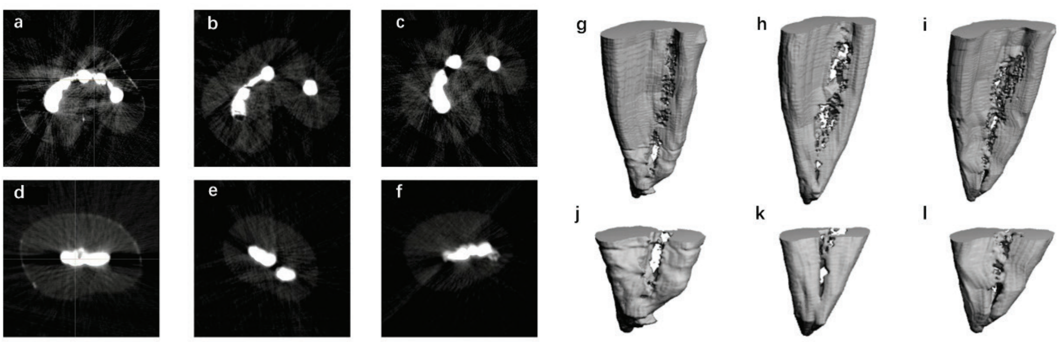

4.

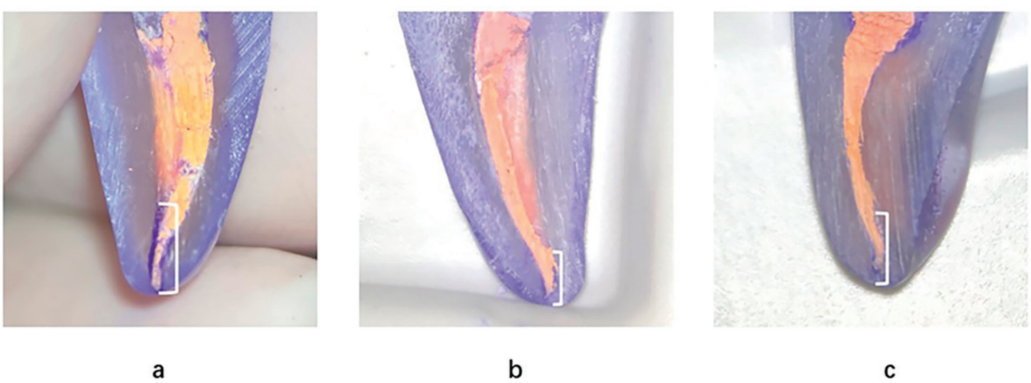

Figure 1 The commoditized 3D-printed resin tooth cross-sectional diagrams.
Slika 1. Dijagrami presjeka zuba od smole isprintanih 3D printanim materijalom
Figure 2 The schematic diagram before/after root canal filling. (a) and (b) before the filling; (c) and (d) after the filling.
Slika 2. Shematski dijagram prije/poslije punjenja korijenskog kanala: (a) i (b) prije punjenja; (c) i (d) poslije punjenja.
Figure 3 Representative Micro-CT reconstructed image. a-c: Cross-sections at 8 mm from the apical foramen in the AHCW, SPSC, and SPCW groups, respectively; d-f: Cross-sections at 3 mm from the apical foramen in the AHCW, SPSC, and SPCW groups, respectively; g-i: 3D reconstruction from 8 mm to the apical foramen (0~8 mm) in the AHCW, SPSC, and SPCW group, respectively; j-l: 3D reconstruction from 3 mm to the apical foramen (0~3 mm) in AHCW, SPSC, and SPCW group, respectively.
Slika 3. Reprezentativna slika rekonstruirana mikro-CT-om. a-c: presjeci na 8 mm od apikalnog foramena u skupinama AHCW, SPSC i SPCW; d - f: presjeci na 3 mm od apikalnog foramena u skupinama AHCW, SPSC i SPCW; g - i: 3D rekonstrukcija od 8 mm do apikalnog foramena (0 – 8 mm) u skupini AHCW, SPSC i SPCW; j - l: 3D rekonstrukcija od 3 mm do apikalnog foramena (0 – 3 mm) u skupinama AHCW, SPSC i SPCW
Figure 4 Photographs of tooth sections stained with gentian violet under the dental microscope: a, AHCW group; b, SPSC group; c, SPCW group.
Slika 4. Fotografije zubnih presjeka obojenih gencijan ljubičastom bojom pod dentalnim mikroskopom: a) AHCW skupina; b) SPSC skupina; c) SPCW skupina

introduced into the canal to sever the master cone, leaving 3~4mm of the remaining gutta-percha mass in the apical section. Warm gutta-percha was then injected into the canals and vertically condensed to complete backfill process.

Group B: iRoot SP by single cone obturation technique (SPSC)

The C-shaped root canals were first fully injected with iRoot SP (Innovative BioCreamix Inc., Vancouver, Canada) using a 24-gauge needle tip provided by the manufacturer. The tip was slowly withdrawn toward the orifice from the point of engagement within the canal. Next, three pieces of 30#/.06 tapered gutta-percha cones were gradually inserted into the canal to the WL. A heat plugger was then used to sever the excess filling material at the root canal orifice level, and the cones were vertically condensed using a cold plugger.

Group C: iRoot SP by continuous wave obturation technique (SPCW)

The C-shaped root canals were first fully injected with iRoot SP using a 24-gauge needle tip provided by the manufacturer. The tip was slowly pulled toward the orifice from the point of engagement in the canal. Three pieces of 30#/.06 tapered gutta-percha cones were then slowly inserted into the canal to the WL. The subsequent procedure employed the same continuous wave obturation technique as group A, where the apical 3~4 mm was filled with the master cone, and the remaining canal region was backfilled with warm gutta-percha.

All the above procedures were performed under a dental microscope (Zumax, Jiangsu, China) with 2× magnification, ensuring each root canal had at least 10 mm of dense filling. Then the cavity was temporarily sealed with cavitation (GC, Japan) and stored in normal saline at 37°C for 7 days.

Micro-CT scan

The samples were scanned by Micro-CT (SCANCO Medical AG, Brüttisellen, Switzerland) at 70kVp, 200uA, AL 0.5mm, 1X300ms with an accuracy of 20um. Scanco Evaluation 1.1.19.0 software was used for 3D reconstruction and measurements. For each sample, the overall root canal filling was evaluated from 8 mm to the apical foramen (0~8 mm), with a specific focus on the apical segment from 3 mm to the foramen (0~3 mm) in the C-shaped root canal. By manually adjusting the threshold method, the volume of root canal filling and its porosity were measured (14). This process began with setting a higher initial threshold and then gradually lowering it until the image clearly displayed the size and shape of the root canal. The threshold value was ultimately determined to be 100 units. The software calculated the volume of the region with a density lower than 100 units, which was considered the unfilled region and recorded as V1. The total volume of the entire measured area was recorded as V. The porosity, representing the ratio of the unfilled volume to the total volume, was calculated using the formula: (V1/V*100%).

sača topline B&L-alpha (B&L, Biotech Inc Koreja) da bi se razrezao glavni konus, ostavljajući od 3 do 4 mm preostale mase gutaperke u apikalnom dijelu. Topla gutaperka zatim je ubrizgana u kanale i vertikalno kondenzirana kako bi se dovršio proces zatrpavanja.

Skupina B: iRoot SP tehnikom opturacije jednim konusom (SPSC)

U korijenske kanale u obliku slova C najprije je ubrizgan cijeli iRoot SP (Innovative BioCreamix Inc., Vancouver, Kanada) s pomoću vrha igle kalibra 24 koju je osigurao proizvođač. Vrh je polako povučen prema otvoru od točke dodira unutar kanala. Zatim su tri komada konusnih gutaperki promjera 30#/.06 postupno umetnuta u kanal do WL-a. Nakon toga je toplinskim čepom uklonjen višak materijala za punjenje na razini otvora korijenskog kanala, a konusi su vertikalno kondenzirani s pomoću hladnog čepa.

Skupina C: iRoot SP tehnikom kontinuiranoga vala opturacije (SPCW)

Korijenski kanali u obliku slova C najprije su u cijelosti injektirani s iRoot SP-om s pomoću vrha igle kalibra 24 koju je osigurao proizvođač. Vrh je polako povučen prema otvoru od mjesta ulaska u kanal. Tri komada gutaperki konusa 30#/.06 zatim su polako umetnuta u kanal do WL-a. Sljedeći postupak koristio se istom tehnikom kontinuiranoga vala opturacije kao i skupina A, u kojoj je apikalnih od 3 do 4 mm ispunjeno glavnim konusom, a preostalo područje kanala ispunjeno je toplom gutaperkom.

Svi gore navedeni postupci obavljeni su pod dentalnim mikroskopom (Zumax, Jiangsu, Kina) s povećanjem od dva puta, osiguravajući da svaki korijenski kanal ima najmanje 10 mm gustog punjenja. Zatim je šupljina privremeno zatvorena kavitacijom (GC, Japan) i pohranjena 7 dana u normalnoj fiziološkoj otopini na temperaturi od 37 °C.

Mikro-CT skeniranje

Uzorci su skenirani Mikro-CT-om (SCANCO Medical AG, Brüttisellen, Švicarska) pri 70 kVp, 200 µA, AL 0,5 mm, 1 x 300 ms s točnošću od 20 µm. Za 3D rekonstrukciju i mjerenja korišten je softver Scanco Evaluation 1.1.19.0. Za svaki uzorak procijenjeno je ukupno punjenje korijenskog kanala od 8 mm do apikalnog foramena (0 – 8 mm), s posebnim naglaskom na apikalni segment od 3 mm do foramena (0 – 3 mm) u korijenskom kanalu u obliku slova C. Ručnim podešavanjem metode praga izmjereni su volumen punjenja korijenskog kanala i njegova poroznost (14). Taj proces počeo je postavljanjem višega početnoga praga, a zatim se postupno snižavao dok slika nije jasno prikazala veličinu i oblik korijenskog kanala. Vrijednost praga konačno je određena na 100 jedinica. Softver je izračunao volumen područja s gustoćom manjom od 100 jedinica koje se smatralo neispunjenim područjem i zabilježeno je kao V1. Ukupni volumen cijeloga izmjerenog područja zabilježen je kao V. Poroznost, koja je omjer neispunjenoga volumena i ukupnoga volumena, izračunata je s pomoću formule (V1/V*100 %).

Dye penetration test

Ten samples from each group were randomly selected for the dye penetration test. The samples were immersed in a 2% gentian violet solution and incubated at 37°C for 7 days. After rinsing with tap water for 15 minutes, the samples were dried. Each sample was sectioned along the long axis of the tooth to the apical foramen at a consistent horizontal level, with the remaining root length standardized to 10 mm. Under a dental microscope (Zumax, Jiangsu, China) at 2× magnification, the distance between the deepest point of dye penetration and the apical foramen was measured using a vernier caliper (15, 16).

Statistical analysis

All statistical analyses were performed using SPSS 26.0 (SPSS Inc., Chicago, IL, USA). Before performing ANOVA, data normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were confirmed. Post-hoc pairwise comparisons were performed using the Least Significant Difference (LSD) method. *P* value of less than 0.05 was considered statistically significant. For key indicators showing significant differences with LSD, the Tukey HSD correction was further applied to control for Type I error.

Results

Micro-CT analysis

In each group, four samples were excluded due to incomplete scanning or significant artifacts, resulting in 16 samples being included in the final analysis. The porosity results are presented in Table 1.

As for the porosity within 8mm from apical foramen, AHCW had the lowest porosity ($P<.05$). Although the average porosity of SPSC was higher than that of SPCW, the difference was not statistically significant ($P=0.617$). For the porosity within 3 mm from the apical foramen, the AHCW group also showed lower porosity compared to other two groups; however, the differences were not statistically significant. Figure 3 displays the relevant images: cross-sectional micro-CT images at 8mm from the apical foramen (a-c), and 3D reconstructions from 8 mm to the apical foramen (g-i). Correspondingly, images at 3mm from the apical foramen are shown (d-f), with 3D reconstructions from 3 mm to the apical foramen (j-l).

Test penetracije boje

Deset uzoraka iz svake skupine nasumično je odabrano za test penetracije boje. Uzorci su uronjeni u 2-postotnu otopinu gencijan violeta i inkubirani 7 dana na temperaturi od 37 °C. Nakon 15-minutnoga ispiranja vodom iz slavine, uzorci su osušeni. Svaki uzorak razrezan je duž duge osi zuba do apikalnog foramena na konzistentnoj horizontalnoj razini, s preostalom duljinom korijena standardiziranom na 10 mm. Pod dentalnim mikroskopom (Zumax, Jiangsu, Kina) pri povećanju od dva puta, udaljenost između najdublje točke penetracije boje i apikalnog foramena izmjerena je kaliperom (15, 16).

Statistička analiza

Sve statističke analize obavljene su u programu SPSS 26.0 (SPSS Inc., Chicago, IL, SAD). Prije upotrebe ANOVA-e potvrđena je normalnost podataka (Shapiro-Wilkov test) i homogenost varijance (Leveneov test). Post-hoc usporedbe parova provedene su korištenjem metode najmanje značajne razlike (LSD). Vrijednost P manja od 0,05 smatrana je statistički značajnom. Za ključne pokazatelje koji ističu značajne razlike s LSD-om, dodatno je primijenjena Tukeyjeva HSD korekcija za kontrolu pogreške tipa I.

Rezultati

Mikro-CT analiza

Iz svake skupine četiri uzorka isključena su zbog nepotpunog skeniranja ili značajnih artefakata, što je rezultiralo uključivanjem 16 uzoraka u konačnu analizu. Rezultati poroznosti nalaze se u tablici 1.

Kad je riječ o poroznosti unutar 8 mm od apikalnog foramena, AHCW je imao najnižu ($P < 0,05$). Iako je prosječna poroznost SPSC-a bila veća od one SPCW-a, razlika nije bila statistički značajna ($P = 0,617$). Za poroznost unutar 3 mm od apikalnog foramena, AHCW skupina također je pokazala nižu poroznost u usporedbi s drugim dvjema skupinama, no razlike nisu bile statistički značajne. Slika 3. – presjek mikro-CT slika na 8 mm od apikalnog foramena (a – c) i 3D rekonstrukcije od 8 mm do apikalnog foramena (g – i). U skladu s tim, prikazane su slike na 3 mm od apikalnog foramena (d – f), s 3D rekonstrukcijama od 3 mm do apikalnog foramena (j – l).

Table 1 The results of porosity within 3/8mm from the apical foramen.
Tablica 1. Rezultati poroznosti unutar 3/8 mm od apikalnog foramena

Apical	Group	Sample size	Porosity (V1/V*100%)	ANOVA P value
8 mm	A. AHCW	16	5.17% (3.44%-6.90%)	0.000
	B. SPSC	16	9.02% (7.54%-10.51%)	
	C. SPCW	16	8.55% (7.58%-9.51%)	
3mm	A. AHCW	16	10.88% (5.28%-16.48%)	0.706
	B. SPSC	16	13.28% (8.71%-17.86%)	
	C. SPCW	16	12.38% (10.21%-14.54%)	

LSD: Group P Value (8mm): A vs B = 0.000, A vs C = 0.001, B vs C = 0.617
Tukey HSD: Group P Value (8mm): A vs B = 0.001, A vs C = 0.003, B vs C = 0.87
Group P Value (3mm): A vs B = 0.411, A vs C = 0.608, B vs C = 0.755

Table 2 The average penetration distance of the three groups
Tablica 2. Prosječna udaljenost prodiranja triju skupina

Apical	Group	Sample size	Penetration distance (mm)	P value
3mm	A. AHCW	10	2.74 (1.76-3.72)	0.714
	B. SPSC	10	2.58 (2.08-3.09)	
	C. SPCW	10	2.37 (1.80-2.94)	

Group P Value: A vs B = 0.418, A vs C = 0.730, B vs C = 0.639

Dye penetration test

The representative photographs of tooth sections stained with gentian violet are shown in Figure 4. The average penetration distances for the three groups are presented in Table 2. ANOVA analysis revealed no significant differences among the three groups, and pairwise comparisons also showed no statistically significant differences.

Test penetracije boje

Reprezentativne fotografije zubnih presjeka obojenih encijan ljubičastom bojom prikazane su na slici 4. Prosječne udaljenosti penetracije za tri skupine nalaze su u tablici 2. Analiza ANOVA-e nije pokazala značajne razlike među triju skupina, a parne usporedbe također nisu pokazale statistički značajne razlike.

Discussion

Based on the results, the null hypothesis was rejected for the overall 0–8 mm porosity, as AHCW showed significantly lower porosity than SPSC and SPCW. However, for the apical 0–3 mm porosity and dye penetration, no significant differences were observed, and the null hypothesis was accepted.

Most previous studies of C-shaped root canals used natural molars to reproduce a clinical situation (17-19), leading to sample inconsistency and potential bias in results. In addition, differences in study designs, materials, and evaluation methods may contribute to the variation in findings. Karatekin et al. compared the obturation quality of continuous wave (CW) and lateral condensation (LC) using 3D-printed resin teeth, and the results showed no difference in porosity(7), while Gok et al. study showed that CW produced more porosity (8). Furthermore, these studies relied primarily on cross-sectional imaging to estimate porosity and focused on a limited range of techniques, omitting commonly used approaches such as the single-cone obturation method (20).

This study utilized 3D-printed resin teeth as substitutes for extracted human teeth, thus minimizing biases related to anatomical variability. This approach aligns with prior research on C-shaped root canal obturation (7, 8). Additionally, the specific morphology of the C-shaped canals in this study was carefully considered. C-shaped root canals exhibit significant morphological variations at different levels. Efforts to establish classification systems aim to facilitate academic and clinical communication while standardizing treatment protocols. Fan's anatomical classification (21), a modification of Melton's system, categorizes C-shaped canals into five types: Type I (C1) - continuous "C" shape, Type II (C2) - semicolumn morphology, Type III (C3) - two or three discrete canals, Type IV (C4) - a single round or oval canal in cross-section, and Type V (C5) - absence of a visible canal lumen. Melton et al. identified Type II (C2) as the most prevalent (22). Furthermore, Seo et al. observed that C-shaped root canals often divide into two or three separate canals in the apical region (23). Therefore, this study selected

Rasprava

Na temelju rezultata nulta hipoteza je odbačena za ukupnu poroznost od 0 do 8 mm, zato što je AHCW pokazao značajno nižu poroznost od SPSC-a i SPCW-a. Međutim, za apikalnu poroznost od 0 do 3 mm i prodiranje boje nisu uočene značajne razlike pa je nulta hipoteza prihvaćena.

U većini dosadašnjih studija o korijenskim kanalima u obliku slova C korišteni su prirodni kutnjaci za reprodukciju kliničke situacije (17 – 19), što je rezultiralo nedosljednošću uzoraka i potencijalnom pristranošću u rezultatima. Uz to, razlike u dizajnu studija, materijalima i metodama evaluacije mogu pridonijeti varijacijama u nalazima. Karatekin i suradnici usporedili su kvalitetu opturacije kontinuiranoga vala (CW) i lateralne kondenzacije (LC) korištenjem 3D printanih zuba od smole, a rezultati nisu pokazali razliku u poroznosti (7). U studiji Goka i suradnika istaknuto je pak da CW proizvodi veću poroznost (8). Nadalje, autori tih studija oslanjali su se uglavnom na snimanje presjeka za procjenu poroznosti i usredotočili su se na ograničeni raspon tehnika, a izostavljali su uobičajeno korištene pristupe poput metode opturacije jednim konusom (20).

U ovoj studiji korišteni su 3D printani zubi od smole kao zamjena za izvađene ljudske zube, čime je minimizirana pristranost povezana s anatomskom varijabilnosti. Taj pristup u skladu je s dosadašnjim istraživanjima o opturaciji korijenskih kanala u obliku slova C (7, 8). Osim toga, u ovoj studiji pozorno je razmotrena specifična morfologija kanala u obliku slova C. Korijenski kanali u tom obliku pokazuju značajne morfološke varijacije na različitim razinama. Napori za uspostavljanje klasifikacijskih sustava imaju za cilj olakšati akademsku i kliničku komunikaciju uz standardizaciju protokola liječenja. Fanova anatomska klasifikacija (21), modifikacija Meltonova sustava, kategorizira kanale u obliku slova C u pet tipova: tip I (C1) – kontinuirani oblik „C", tip II (C2) – morfologija polustupa, tip III (C3) – dva ili tri diskretna kanala, Tip IV (C4) – jedan okrugli ili ovalni kanal u presjeku i tip V (C5) – odsutnost vidljivoga lumena kanala. Melton i suradnici identificirali su tip II (C2) kao najrasprostranjeniji (22). Nadalje, Seo i suradnici uočili su da se korijenski kanali u obliku slova C često dijele u dva ili tri odvoje-

3D-printed resin teeth with C2 morphology in the middle and upper segments of the root canal and C3 morphology in the apical segment, reflecting these findings.

Micro-CT is a widely recognized method for assessing root canal obturation quality (13). However, its application to C-shaped canals presents challenges, primarily due to artifacts from high-density filling materials (24). C-shaped canals require more gutta-percha than other canal types, resulting in increased artifacts (25). Additionally, overlapping artifacts during image reconstruction further compromise accuracy. The complex morphology of C-shaped canals amplifies their impact (14). To reduce artifact interference, we conducted a dye penetration test, providing a direct evaluation of sealing quality. While Micro-CT infers sealing quality indirectly through porosity, this combined approach ensures a more accurate and practical assessment.

Our findings indicated that when using the continuous wave obturation technique, iRoot SP could not achieve the same outcomes as AH Plus in the 0~8mm area (5.17% VS 8.55%, P<0.05). Within the apical segment (0~3mm), the porosity of AHCW and SPCW were not statistically significant, and this was also confirmed by the dye penetration test. Our research results differ from the previous findings on the single-canal. Previous research on the porosity of iRoot SP and AH Plus in human lower incisors revealed that, the obturation quality of AH Plus and iRoot SP show no statistically significant differences at any level of the root canal (26). Another study conducted in 2021 compared sealer penetration on single-rooted extracted teeth. The results indicated that there was no statistically significant difference between the AH Plus and iRoot SP group with the continuous wave condensation technique (27).

This difference may be attributed to the flowability of different sealers and the complex anatomical structure of C-shaped canals. Temperature has a significant and non-negligible influence on the fluidity of root filling materials. Kurt and Hazar Bodrumlu demonstrated that temperature significantly affects the flowability and X-ray opacity of calcium hydroxide root canal paste (28). Similarly, under conditions of 37°C and 95% relative humidity (RH), both AH Plus and iRoot SP exhibited similar levels of fluidity, but as the temperature increased, the fluidity of AH Plus increased while that of iRoot SP decreased(29). Hence, AH Plus demonstrates superior fluidity and is more adept at accessing the narrow isthmus within the root canal in a high-temperature environment. Additionally, it is worth noting that the curing time of iRoot SP in a physiological environment is approximately (2.7±0.3) hours (29). However, it is important to note that Qu et al. discovered that the curing time of iRoot SP decreases as the temperature increases (30). The setting time of iRoot SP exhibited a notable decrease, going from (245.8 ± 15.9) minutes at 37°C to just (14.2 ± 0.6) minutes at 140°C. In instances where gutta-percha was heated at the apical segment or hot gutta-percha was injected, the sealer was also affected by the high temperature, leading to reduced sealer fluidity and premature curing. This hindered iRoot SP from adequately filling narrow areas such as isthmuses and lateral canals. Consequently, AH Plus outperformed iRoot SP in

na kanala u apikalnom području (23). Zato su za ovu studiju odabrani 3D printani zubi od smole s C2 morfologijom u srednjem i gornjem segmentu korijenskog kanala i C3 morfologijom u apikalnom segmentu, što slijedi te nalaze.

Mikro-CT široko je priznata metoda za procjenu kvalitete opturacije korijenskog kanala (13). No njegova je primjena na kanale u obliku slova C izazov, ponajprije zbog artefakata od materijala za punjenje visoke gustoće (24). Kanali u obliku slova C zahtijevaju više gutaperke od drugih vrsta kanala, što rezultira povećanim artefaktima (25). Uz to, preklapanje artefakata tijekom rekonstrukcije slike dodatno ugrožava točnost. Složena morfologija kanala u obliku slova C pojačava njihov utjecaj (14). Kako bismo smanjili interferenciju artefakata, primijenili smo test penetracije boje, pružajući izravnu procjenu kvalitete brtvljenja. Dok mikro-CT neizravno zaključuje o kvaliteti brtvljenja na temelju poroznosti, ovaj kombinirani pristup osigurava točniju i praktičniju procjenu.

Naši nalazi upućuju na to da pri korištenju tehnike kontinuiranoga vala opturacije, iRoot SP nije mogao postići iste rezultate kao AH Plus u području od 0 do 8 mm (5,17 % u odnosu prema 8,55 %, P < 0,05). Unutar apikalnog segmenta (0 – 3 mm), poroznost AHCW-a i SPCW-a nije bila statistički značajna, što je potvrđeno i testom penetracije boje. Naši rezultati istraživanja razlikuju se od dosadašnjih nalaza na jednom kanalu. Dosadašnja istraživanja o poroznosti iRoot SP-a i AH Plusa na donjim sjekutićima kod ljudi otkrila su da kvaliteta opturacije AH Plusa i iRoot SP-a ne pokazuje statistički značajne razlike ni na jednoj razini korijenskog kanala (26). U drugoj studiji iz 2021. godine uspoređena je penetracija punila na zubima s jednim korijenom. Rezultati su pokazali da nije bilo statistički značajne razlike između skupine AH Plus i iRoot SP s tehnikom kontinuiranoga vala kondenzacije (27). Ta razlika može se pripisati tečnosti različitih punila i složenoj anatomskoj strukturi kanala u obliku slova C. Temperatura značajno i nezanemarivo utječe na tečnost materijala za punjenje korijenskog kanala. Kurt i Hazar Bodrumlu pokazali su da temperatura značajno utječe na tečnost i rendgensku neprozirnost paste za korijenski kanal s kalcijevim hidroksidom (28). Slično tomu, u uvjetima s temperaturom od 37 °C i 95 % relativne vlažnosti (RH), i AH Plus i iRoot SP pokazali su sličnu razinu tečnosti, ali kako se temperatura povećavala, tako se povećavala tečnost AH Plusa, a iRoot SP-a se smanjivala (29). Zato AH Plus pokazuje superiorniju tečnost i vještiji je u pristupu uskom izmu unutar korijenskog kanala u okruženju s visokom temperaturom. Uz to, valja napomenuti da je vrijeme stvrdnjavanja iRoot SP-a u fiziološkom okruženju približno (2,7 ± 0,3) sata (29).

No važno je napomenuti da su Qu i suradnici otkrili da se vrijeme stvrdnjavanja iRoot SP-a smanjuje s porastom temperature (30). Vrijeme stvrdnjavanja iRoot SP-a pokazalo je značajno smanjenje, s (245,8 ± 15,9) minuta na 37 °C na samo (14,2 ± 0,6) minuta na 140 °C. U slučajevima kada je gutaperka zagrijana u apikalnom segmentu ili je ubrizgana vruća, na brtvilo je također utjecala visoka temperatura, što je smanjilo njegovu fluidnosti i potaknulo prerano stvrdnjavanje. To je spriječilo iRoot SP da adekvatno ispuni uska područja poput istmusa i lateralnih kanala. Posljedično, AH terms of filling density when employing the continuous wave obturation technique.

Furthermore, Micro-CT results indicated that SPSC exhibited higher porosity than SPCW in the 0–8 mm region and the 0–3 mm apical segment, although these differences were not statistically significant. Similarly, the dye penetration test showed no difference in sealing performance between the two techniques. These findings raise interesting points when compared to previous studies. One study comparing warm gutta-percha and cold gutta-percha techniques (single cone) in single-rooted teeth found both methods to be comparable in terms of filling percentage and void distribution (31). Similarly, another study demonstrated that both single cone (SC) and continuous wave (CW) techniques effectively filled single-rooted canals with lateral canals (32). However, Yu et al. evaluated the efficacy of filling isthmuses in root canals using AH Plus, GuttaFlow2, and iRoot SP with either CWC or SC techniques (33). Their results revealed that SC was more prone to significant voids in the isthmus region, particularly in the apical area, whereas CW achieved a higher percentage of filled area compared to SC(33). We speculate that the differences in the above results stem from the fact that the first two studies focused on single-canal systems, while the latter study and our study used more complex root canal models.

In summary, our findings provide practical guidance for the clinical management of C-shaped canals. Clinicians may consider using AH Plus in conjunction with the continuous wave technique to achieve denser and more reliable root canal obturation, while iRoot SP remains a viable alternative due to its favorable biocompatibility and osteogenic potential. Caution is warranted when employing the single-cone technique, as it may inadequately adapt to complex anatomical configurations. Achieving a complete apical seal continues to pose a significant clinical challenge, which could be mitigated through meticulous canal cleaning, ultrasonic activation of irrigants, and optimized obturation strategies.

However, the limitations of this study must be acknowledged. Current technology does not allow for the complete replication of the texture, hardness, and intricate structures, such as dentinal tubules, found in natural teeth. Additionally, it cannot fully reproduce the chemical and physical interactions between biomaterials and dentin. Overcoming these limitations depends on future advancements in 3D printing technology and materials.

Conclusion

Among the three root canal filling techniques evaluated in this study, the continuous wave obturation technique with AH Plus (AHCW) achieved the highest density of root canal filling, particularly in the middle and upper segments. However, no significant differences were observed in the obturation quality of the apical segments among the three techniques.

Plus je nadmašio iRoot SP kad je riječ o gustoći punjenja pri korištenju tehnike opturacije kontinuiranim valovima.

Nadalje, rezultati mikro-CT-a pokazali su da SPSC pokazuje veću poroznost od SPCW-a u području od 0 do 8 mm i apikalnom segmentu od 0 do 3 mm, iako te razlike nisu bile statistički značajne. Slično tomu, test penetracije boje nije pokazao razliku u učinkovitosti brtvljenja između dviju tehnika. Ti nalazi ističu zanimljive točke u usporedbi s dosadašnjim studijama. Autori jedne studije u kojoj su se uspoređivale tehnike tople i hladne gutaperke (jedan konus) u zubima s jednim korijenom otkrili su da su obje metode usporedive kad je riječ o postotku punjenja i raspodjeli šupljina (31). Slično tomu, u drugoj studiji istaknuto je da su i tehnike jednog konusa (SC) i tehnike kontinuiranoga vala (CW) učinkovito ispunile kanale s jednim korijenom s lateralnim kanalima (32). No, Yu i suradnici procijenili su učinkovitost punjenja istmusa u korijenskim kanalima koristeći se AH Plusom, GuttaFlowom2 i iRoot SP-om s tehnikama CWC ili SC (33). Njihovi rezultati otkrili su da je SC bio skloniji većim šupljinama u području istmusa, posebno u apikalnom području, a CW je postigao veći postotak ispunjenog područja u usporedbi sa SC-om (33). Pretpostavljamo da razlike u navedenim rezultatima nastaju zbog činjenice da su se autori prvih dviju studija usredotočili na sustave s jednim kanalom, a posljednja spomenuta i naša studija koristile su se složenijim modelima korijenskog kanala. Ukratko, naši nalazi daju praktične smjernice za kliničko liječenje kanala u obliku slova C. Kliničari mogu razmotriti korištenje AH Plusa u kombinaciji s tehnikom kontinuiranoga vala kako bi postigli gušću i pouzdaniju opturaciju korijenskog kanala, a iRoot SP ostaje održiva alternativa zbog povoljne biokompatibilnosti i osteogenoga potencijala. Potreban je oprez pri primjeni tehnike jednog konusa jer se ona može nedovoljno prilagoditi složenim anatomskim konfiguracijama. Potpunog apikalno brtvljenje i dalje je golem klinički izazov koji se može ublažiti pažljivim čišćenjem kanala, ultrazvučnom aktivacijom iriganata i optimiziranim strategijama opturacije.

No moraju se priznati i ograničenja ove studije. Trenutačna tehnologija ne omogućuje potpunu replikaciju teksture, tvrdoće i složenih struktura, poput dentinskih tubula, koje se nalaze u prirodnim zubima. Uz to, ne može u cijelosti reproducirati kemijske i fizičke interakcije između biomaterijala i dentina. Prevladavanje tih ograničenja ovisi o budućem napretku u tehnologiji 3D ispisa i materijalima.

Zaključak

Među trima tehnikama punjenja korijenskog kanala procijenjenih u ovoj studiji, tehnika kontinuiranoga vala opturacije s AH Plusom (AHCW) postigla je najveću gustoću, posebno u srednjem i gornjem segmentu. No nisu uočene značajne razlike u kvaliteti opturacije apikalnih segmenata između triju tehnika.

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Sažetak

Svrha: Željelo se procijeniti kvalitetu opturacije kanala u 3D printanim kanalima u obliku slova C korištenjem Mikro-CT-a i penetracijom boje s različitim tehnikama punjenja. **Metodologija:** Šezdeset 3D printanih zuba s kanalima u obliku slova C opturirano je korištenjem AH Plusa s kontinuiranim valom (AHCW), iRoot SP-a s jednim konusom (SPSC) te iRoot SP-a s kontinuiranim valom (SPCW). Mikro-CT korišten je za 3D rekonstrukciju u dvama područjima: 0 do 8 mm (ukupni kanal) i 0 do 3 mm (apikalni segment). Volumen šupljina (V1) i ukupni volumen kanala (V) poslužili su za izračun poroznosti kao (V1/V) × 100 %. Kvaliteta brtvljenja procijenjena je penetracijom boje. **Rezultati:** Rezultati su pokazali da AHCW postiže značajno nižu poroznost unutar 8 mm (5,17 %) u usporedbi sa SPSC-om (9,02 %) i SPCW-om (8,55 %), (P < 0,5). Nisu uočene značajne razlike u poroznosti unutar 3 mm ili u prodiranju boje. **Zaključak:** AHCW je postigao bolju opturaciju u srednjem i gornjem segmentu, bez većih razlika među tehnikama u apikalnome segmentu.

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MeSH pojmovi: priprema korijenskog kanala; trodimenzionalni ispis; punjenje korijenskog kanala
Autorske ključne riječi: kanal u obliku slova C; tehnika opturacije kontinuiranim valom; tehnika opturacije jednim konusom; 3D printani zubi od smole

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