European Journal of Prosthodontics and Restorative Dentistry (2024) 32, 109–119

Micromorphology of Root Canal Walls After Laser Activated Irrigation

Keywords

Laser
Disinfection
Endodontics
Activated Irrigation
Smear-Layer

Authors

Clara I. Anton y Otero *
(Dr med. dent)

Laurine Marger *
(Dr)

Albert Feilzer §
(Professor)

Ivo Krejci *
(Professor)

Marwa Abdelaziz *
(PhD)

Address for Correspondence

Clara I. Anton y Otero *

Email: clara.antonyotero@unige.ch

* Division of Cariology and Endodontology, CUMD - University Clinics of Dental Medicine, Faculty of Medicine, University of Geneva, Geneva, Switzerland

§ Department of Dental Material Sciences, Academic Center for Dentistry Amsterdam (ACTA) - Gustav Mahlerlaan 3004, 1081 LA Amsterdam

Received: 19.07.2023
Accepted: 17.10.2023

doi: 10.1922/EJPRD_2600AntonyOtero11

ABSTRACT

This study aims to investigate the effects of laser-activated irrigation on root canal dentin using different laser wavelengths. Sixty-six roots were prepared and split longitudinally. First, lasers with different power settings were tested on 34 samples, pre-etched with phosphoric acid, or remaining with a smear-layer to determine the test parameters. Selected parameters were then applied on thirty roots (9 groups) covered with smear layer: 1. Smear-layer removed; 2. Smear-layer untouched; 3. Conventional needle irrigation with NaOCl and EDTA; 4. ER:YAG laser; 5. 9.3 µm CO_2 laser; 6-9. Diode lasers. All lasers were applied in ultra-pure water as an irrigant. Root halves were examined by scanning electron microscope to analyze the intracanal dentin micromorphology on 9 consequent photos per specimen @ a magnification of 1000X. The results showed that conventional needle irrigation was effective in removing the smear-layer from coronal and middle root parts, while laser-activated irrigation had two main mechanisms: cleaning and opening of the dentinal tubules by removing the smear layer (Er:YAG laser) and melting of dentin (CO_2 and diode lasers) in all root parts. The study concluded that laser-activated irrigation with different wavelengths impacted the smear layer and root canal dentin differently through pure physical/mechanical effects.

INTRODUCTION

A successful root canal treatment aims to establish and maintain a clean, sterile, and infection-free root canal system. Achieving this goal involves not only shaping the main root canal but also removing the smear layer containing bacteria and their by-products. Several studies have reported that the removal of the smear layer is a critical factor in the success of endodontic treatment.[1,2] Additionally, removing the smear layer allows disinfectants to penetrate the root canal walls, which are composed of dentin with numerous tubules that may harbor pulpal cells and microbial remnants.[3-5]

An ideal irrigant should have a broad antimicrobial spectrum and could dissolve necrotic pulp tissue remnants, inactivate endotoxins and remove the smear layer after instrumentation.[6] Sodium hypochlorite (NaOCl) is widely used due to its antimicrobial effects and tissue dissolution properties. However, to effectively remove the smear layer and debris, it must be used in combination with another irrigant, such as Ethylenediaminetetraacetic acid (EDTA), that can dissolve inorganic components.[7-9] Despite the mechanical preparation and use of irrigants such as NaOCl and EDTA, literature has shown, that complete removal of the smear layer and biofilm from the entire root canal walls, particularly in the apical root third is challenging due to anatomic factors.[4,10-20] The apical root third is narrow and challenging to reach by irrigants due to a phenomenon called apical vapor lock, a gas entrapment in the root canal.[18] As roots are surrounded by the periodontal ligament hindering irrigant apical extrusion, the system behaves as a close-ended channel. This is why irrigants always exit the canal coronally rather than apically or laterally. Disrupting the surface tension at the apical solution–air interface, an action necessary for the displacement of the apically located air towards the solution, is therefore challenging.[21,22]

Laser-activated irrigation (LAI) has been reported in the literature as a promising technique for enhancing homogeneous cleaning of the root dentin walls independent of root canal anatomy.[23-26] However it is still unclear, whether the promising results regarding smear-layer removal are due to the mechanical effect of the laser cavitation or a synergistic effect of both chemical and mechanical action.

The laser energy, that is absorbed in the irrigant induces the formation of small vapor-filled bubbles and cavitation. The collapse of the bubbles in the liquid leads to shock waves, that results in streaming of the irrigant. The irrigant movements contribute to the disruption of the apical vapor surface and promote irrigant flush to the apex.[27]

In the field of LAI, infrared lasers with wavelengths between 1400 nm to 3000 nm, such as Er:YAG with 2940 nm, are well investigated as their wavelengths are perfectly absorbed in water.[28,29]

Far infrared lasers as 9300 nm CO_2 lasers coincide equally well with the absorption bands of water and have shown promising results for LAI in artificial models.[30] However, up to date there is only few literature on CO_2 lasers investigating their application for activation of irrigants in endodontics.

Additionally, literature suggests, that diode lasers with near infrared wavelengths (as for instance with 980 nm) applied with high energy parameters can improve the action of disinfection and chelating agents for smear layer removal from dentinal root walls.[31] These results were however not promising for the clinical application since the laser effects on the irrigants were limited due to the low absorption and high laser power parameters needed.

A recent study found cavitation to be possible with low power parameters if the laser tip is black-coated. With this method, the laser tips is used as a heater and leads therefore to vapor bubble formation and consequent streaming in the irrigant.[30]

In this study we aimed to investigate solely mechanical effects of LAI of ultra-pure water with a 9300 nm CO_2 and low-power diode lasers with 455 nm, 808 nm, 970, and 980 nm on smear layer removal in comparison to Er:YAG laser application and the conventional chemical-mechanical effects of needle irrigation with NaOCl and EDTA.

The three tested null hypotheses were: 1: LAI with Er:YAG laser would be as effective as conventional chemical-mechanical irrigation in removing the smear layer, 2: Er:YAG and 9300nm CO_2 laser would equally clean dentin root walls from smear layer and debris, and 3: Diode lasers would have the same impact on root canal dentin as the other lasers.

MATERIALS AND METHODS

ROOT CANAL PREPARATION

For this study, 66 caries-free human upper third molars with straight and round-shaped palatal roots were selected. The anonymized teeth were stored in a 0.1% thymol solution at 4°C after extraction until further use. Prior to the experiment, any soft-tissue remnants still adhering to the teeth were removed using an ultrasonic scaler (EMS Piezo Master 400, EMS SA Nyon, Switzerland).

Next, the tooth-crowns were cut at the tooth-neck around the cemento-enamel junction (CEJ) at 12 mm measured from the apex to standardize the root length using a diamond disc (127 mm diameter, X0.4 mm, Cut-off Wheel MOD 13, Struers, Ballerup, Denmark). Access cavities were then finished using a diamond bur with a grit size of 25 µm (Intensiv, Montagnola, Switzerland).

Subsequently, the localization of canal orifices was accomplished, and the size of the apical constriction was controlled with a size 10 and 15 taper C-pilot file (MICRO-MEGA, Besançon Cedex, France), diameters of larger than 15 have been excluded from the study and replaced. The roots were longitudinally cut with the same instrument and both halves were polished with silicon carbide paper (FEPA P120, Struers, Ballerup, Denmark). In order to facilitate the SEM evaluation, a horizontal groove was created on the section surface of the apical 9 mm of the root canal (10 mm of the root length) using a diamond bur (25 µm, Intensive, Montagnola, Switzerland) (*Figure 1*). Both root halves were manually reassembled and secured in place with a flowable composite (Tetric EvoFlow, Schaan, Liechtenstein). The root apices were then sealed with the same composite, both without any adhesive procedures, under a magnification of X16 stereomicroscope (Leica, Wild, Heerbrugg, Switzerland) and impermeability was confirmed. Finally, the teeth were embedded in silicon (Platinum 95, Zhermack, Badia Polesine, Italy).

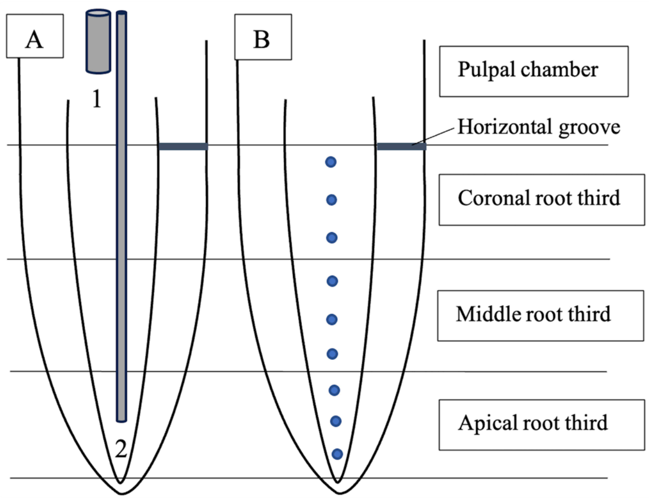


Figure 1: Overview of one root half A: position of laser tips (1: Er:YAG and CO_2 laser, 2: diode lasers) and B: position of photos taken with the SEM.

SHAPING AND CLEANING

Reassembled root canals were prepared using a crown-down technique with a rotary file system (ProTaper Gold, Maillefer Dentsply, Ballaigues Switzerland) and an endodontic motor (x smart plus, Maillefer Dentsply, Ballaigues, Switzerland) up to a working length of 11 mm up to a diameter of F4 (0.40/0.6v) and irrigation with ultra-pure water.

First, we investigated the effects of different laser power parameters *(Table 1)* on 34 root dentin samples. Half of the samples were etched for 60 sec with 35% phosphoric acid (Ultra-Etch, Ultradent, South Jordan, UT, USA) after mechanical preparation and abundantly rinsed for 20 seconds. The other half was left with smear-layer. Each laser with different settings was applied to both, a pre-etched tooth sample and to a sample with heavy smear-layer.

Table 1. Laser settings for Er:YAG, CO_2 and diode lasers.

Laser	Wavelength	Tip	Parameters
Er:YAG laser (Lite Touch III REF LI-FG0012A, Light Instruments, Yokneam, Israel)	2.94 µm	AS7066(X) 1.3×14mm	50 mJ, 15Hz; Ø 0.75W
CO_2 laser (Solea, Convergent Dental, Inc., Natick, MA, USA)	9.3 µm	Ultra-guide handpiece with endo-tip Ø 1.25mm	10% (Ø 0.1W, 14 Hz)
			20% (Ø 0.2W, 14Hz)
			40% (Ø 0.4W. 14Hz)*
			60% (Ø 0,6W, 14Hz)
Diode laser (SIROLASE Blue, Sirona dental systems GmbH, Bensheim, Germany)	455 nm	(Carbon black coated) Endo tip Ø 0.4mm	10% DC, 0.8W, 15Hz Ø 80mW
			40% Duty Cycle, 0.8W, 15Hz Ø 320mW*
			67% Duty Cycle, 0.8W, 15Hz Ø 536mW
Diode laseaser (SIROLASE Blue, Sirona dental systems GmbH, Bensheim, Germany)	970 nm	Carbon black coated) Endo tip Ø 0.4mm	10% Duty Cycle, 0.8W, 15Hz; Ø 80mW
			40% Duty Cycle, 0.8W, 15Hz; Ø 320mW*
			67% Duty Cycle, 0.8W, 15Hz; Ø 536mW
Diode laser (Wiser Dr smile, Lambda SpA, Brendola, Italy)	808 nm	Carbon black coated) Endo tip Ø 0.2mm	750 on, 65916 off, 4W; Ø 0.045W
			26666 on, 40000 off, 1W; Ø 0.40W*
			66667 on, 33333 off, 1W; Ø 0.67W
Diode laser (Wiser Dr smile, Lambda SpA, Brendola, Italy)	980 nm	Carbon black coated) Endo tip Ø 0.2mm	750 on, 65916 off, 4W; Ø 0.045W
			26666 on, 40000 off, 1W; Ø 0.40W*
			66667 on, 33333 off, 1W; Ø 0.67W

Pulse-length: Er:YAG 50ms, CO_2 10% 8µs, 20% 1.6µs, 40% 3.2µs, 60% 4.8µs, diode lasers 1% 0.6ms, 10% 7ms, 40% 27ms, 67% 45ms

CO_2 laser with 40% was applied on two additional pre-etched samples in order to investigate both, the surface pattern and also changes in deeper dentin layers. These samples were therefore additionally split as described in detail in the paragraph concerning preparation for SEM.

Diode laser tips were black coated prior use with carbon particles (Carbon black, acetylene 100%, compressed, 99.9+%, Alfa Aesar, Kandel, Germany) that were glued with a transparent glue-spray (Toolcraft, Conrad Electronic AG, Wollerau, Switzerland). Their tips were inserted up to 9 mm and moved slowly upwards and again downwards with helicoidal movements (1 mm per second) during activation, whereas Er:YAG and CO_2 laser tips were placed in the pulpal chamber during activation.

Based on the above-described preliminary investigations, one laser power parameter was chosen for the following experiments (marked with an asterisk in Table 1).

Based on the results of the first part (a difference of 25% between the positive control and the conventional group in scoring cleared dentin tubules) and a power of 80% as well as a two-sided alpha error of 5% we calculated a sample size of n= 4 teeth per group for the following experiments in 9 groups:

1. Positive control (N=4): Ultra-pure water (10ml), drying the canal with paper points (Large, WaveOne Gold, Dentsply Sirona, Baden, Switzerland), etching the canal walls with 35% H3PO4 (Ultra-Etch, Ultradent, South Jordan, UT, USA) for 60 seconds under constant movements with a paper-point. Rinsing with ultra-pure water (5ml);
2. Negative control smear-layer (N=4): 2ml ultra-pure water between each file and a final rinse with 5ml ultra-pure water;
3. Conventional treatment (N=4): 2ml NaOCl (3%, Hänseler swiss pharma, Herisau, Switzerland) between each file and final flush with 5ml EDTA (17%, pharma24 SA, Geneva, Switzerland) and 5ml ultra-pure water;
4. Er:YAG laser (N=4): 2ml ultra-pure water between each file, 5x 20 seconds of activation of ultra-pure water (5ml) ((AS7066(X), 1.3×14 mm; 50mJ, 15Hz
5. 9.3 µm CO_2 laser (N=4): 2ml ultra-pure water between each file, 5x 20 seconds of activation of water (5ml) (Ultra-guide handpiece with endo-tip Ø 1.25 mm; 40%)
6. SIROLASE 455nm (N=4): 2ml ultra-pure water between each file, 5x 20 seconds of activation of water (5ml) (black coated tip Ø 0.4 mm; 0.8W, 40% duty cycle, 15 Hz)
7. SIROLASE 970nm (N=4): 2ml ultra-pure water between each file, 5x 20 seconds of activation of water (5ml) (black coated tip Ø 0.4 mm; 0.8W, 40% duty cycle, 15 Hz)
8. WISER 808nm (N=4): 2ml ultra-pure water between each file, 5x 20 seconds of activation of water (5ml) (black coated tip Ø 0.2 mm; 1W, 26666µs on, 40000 off)
9. WISER 980nm (N=4): 2ml ultra-pure water between each file, 5x 20 seconds of activation of water (5ml) 40% power (black coated tip Ø 0.2 mm; 1W, 26666µs on, 40000 off)

PREPARATION FOR SEM

After shaping and irrigation, the root canals were dried with paper points (Large, WaveOne Gold, Dentsply Sirona, Baden, Switzerland) and samples unwrapped from silicon and resin composite.

Two additional pre-etched root samples prepared with the CO_2 laser @ 40% power on pre-etched root dentin received a groove with a diamond disk (Diamond Cut-off Wheel M1D13, 127 mm dia. X 0.4 mm, Struers, Ballerup, Denmark) under constant water cooling at the external surface of the root fragment in order to split it in longitudinal direction along the root canal with a hammer and chisel into two.

All samples were subsequently fixed in a solution of 0.1M cacocylate (Sodium cacodylate trihydrate ≥ 98%, Sigma-Aldrich Chemie, Steinheim, Germany) and 2.5% glutaraldehyde (glutaraldehyde solution 50%, Sigma-Aldrich Chemie, Steinheim, Germany) and dried in increasing concentrations of ethanolic solutions (50%, 70%, 90% and 100% Ethanol, EMSURE, Merck KGaA, Darmstadt, Germany). The split root samples were then glued on custom-made specimen holders with a glue (UHU GmbH, Bolton, Switzerland) and further dried in a vacuum desiccator (Kartell S.p.A., Noviglio, Italy) for 7 days.

The dried root halves were then coated with a layer of 50 nm thickness of 24 karat gold using a gold sputter (HHV Ltd, Crawley, UK) before evaluation under scanning electron microscopy (SEM) (Zeiss Gemini-Sigma 300 VP instrument, Karl Zeiss Microscopy, Cambridge, UK). For each specimen, nine photos with a magnification of 1000X were captured in the center of the root halves. This was done by taking three subsequent photos in each root third of 3 mm (apical, middle, and coronal) while excluding the pulpal chamber part and the apical 1 mm of the root canal. (*Figure 1*)

Specimens for investigation of deep root dentin layers were photographed at a magnification of X200 along the longitudinal fracture line.

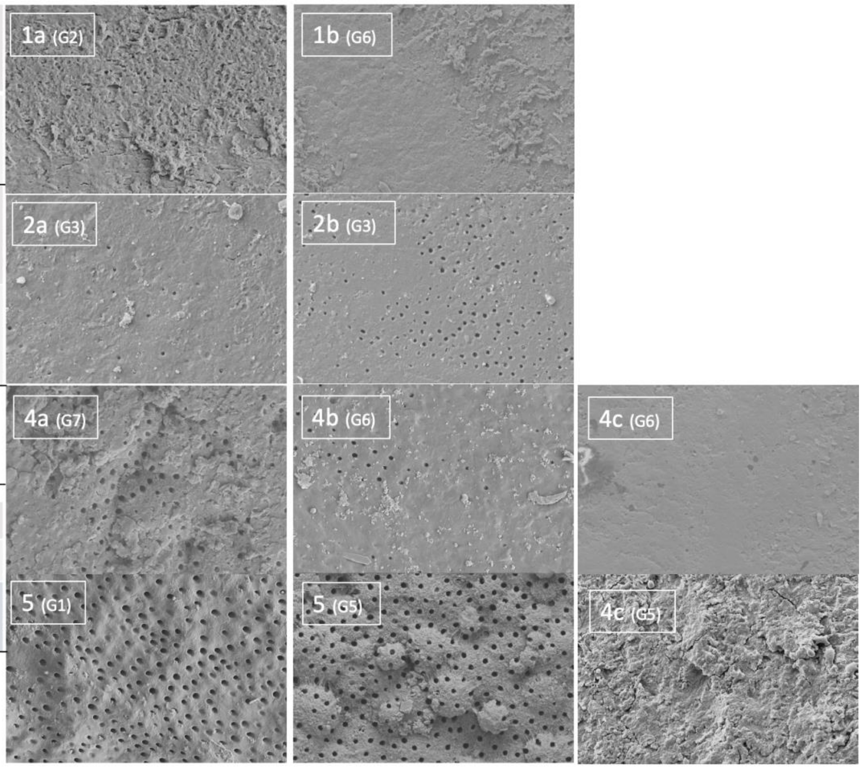
The ultrastructural analysis scores were determined by three independent operators based on the established criteria described in the literature.[32] To ensure consistency and accuracy, the operators were trained with photos from the literature and pilot studies until they reached an agreement on the laser-specific patterns and score attribution. In order to provide a more detailed and precise evaluation, the scoring system was further divided into sub-categories during the calibration phase (*Table 2*).

STATISTICS

Evaluators' scores have been compared using Friedman's ANOVA and the Kendall Coefficient of Concordance with a significance level of 0.05.

Table 2. Score for ultrastructural analysis of root dentin walls after different irrigation protocols with representing examples for each score level @ X1000.

Score	Description	Sub-score	Sub-description
1	**Heavy smear layer covering the specimen; no tubule orifices; regular aspect**	a	no melting and fusion
		b	with signs of melting and fusion
2	**Some smear layer; tubules visible but not completely opened; no visible melting, fusion or erosion**	a	< 1/3 tubules open
		b	1/3 to 2/3 tubules open
3	**Modified organic matrix layer with an amorphous form; tubules visible but not completely opened; no visible melting, fusion or erosion**		
4	**Little or no smear layer, sealed dentin tubules; melting and fusion**	a	< 1/3 tubules/ surface sealed
		b	1/3 to 2/3 tubules/ surface sealed
		c	> 2/3 tubules/surface sealed
5	**little or no smear layer; most tubules visible and opened (> 2/3); erosion**		



RESULTS

EFFECTS OF LASER-ACTIVATED IRRIGATION ON DENTIN MICROMORPHOLOGY WITH AND WITHOUT SMEAR-LAYER WITH DIFFERENT LASERS AND LASER POWER PARAMETERS

The application of LAI in ultra-pure water with Er:YAG laser, CO_2 and diode lasers with the lowest tested power setting on dentin covered with a heavy smear-layer resulted in an incomplete exposure of dentinal tubules entrances. All lasers had either no effect on the smear-layer or removed it partly, exposing only a few dentinal tubules entrances. With CO_2 laser at 10% power, we observed more exposure in the coronal thirds than apically, and diode lasers showing no difference in exposure between root thirds.

When CO_2 laser was set at 20% power, exposed dentinal tubules were mainly visible in the middle root third, while settings at 40% power mainly affected the apical third. With higher power settings, no dentinal tubules were visible. *(Figure 2A)*

Laser pulses with power > 40% were so strong that the irrigant in the pulpal chamber and the root canal evaporated after a few seconds of activation and irrigant had to be added.

With diode lasers, medium values showed equally few exposed dentinal tubules, independent of the root third, but with the lowest and highest parameter settings, dentinal tubules exposure was no longer observed. *(Figure 2A)*

In samples with widely opened tubules, pre-etched with phosphoric acid, LAI with Er:YAG laser, the CO_2 and diode lasers with the lowest power settings did not result in any visible effects. However, CO_2 laser with 20% power showed closed dentinal tubule entrances, primarily concentrated in the coronal root third, while 40% power led to closed dentinal tubule entrances in the middle and coronal regions of the root. CO_2 laser power parameters greater than or equal to 60% resulted in homogeneously smooth patterns with closed dentin tubules throughout the entire root length. Additionally, the melted dentin pattern appeared in lines and the surface area increased with higher power parameters. *(Figure 2B and Figure 3A-D)*

In two additional vertically fractured pre-etched samples, the dentin micromorphology with the CO_2 laser at 40% power was found to be constantly altered up to a depth of 8-12 µm, and the dentinal tubules were not visible and appeared to be melted in this region. *(Figure 3E-F)*

In photos of the main root canal, diode lasers with 40% power showed also melted dentinal tubule entrances. Regardless of the root region, these patterns increased in size with the highest power setting but led to charring and significant heat development at the external root surface. *(Figure 2B)*

Based on the above-described results, we chose medium power settings for CO_2 and diode lasers for the second part of the study.

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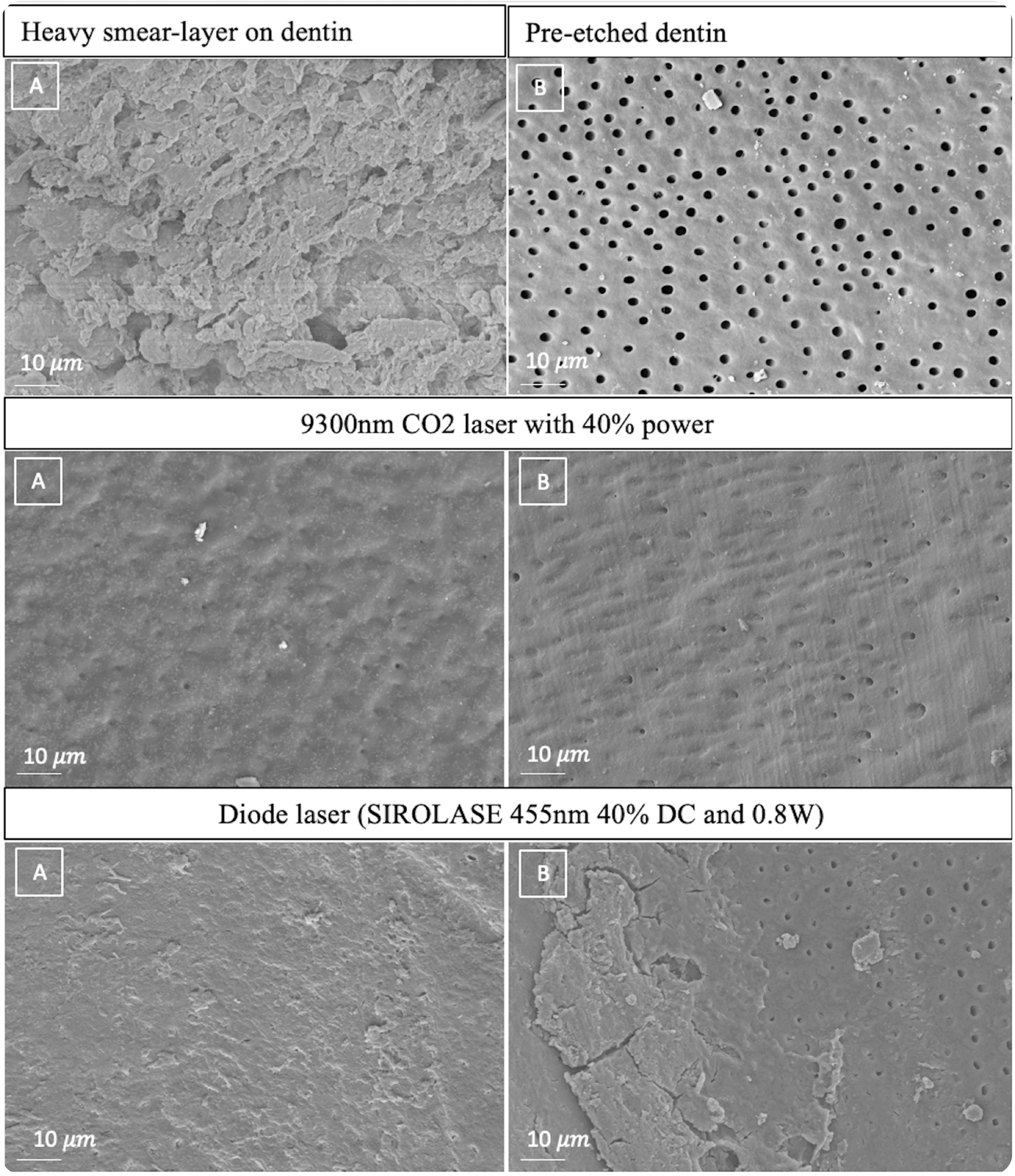

Figure 2: SEM images X 1000 with laser effects on smear-layer (A) and etched dentin (B) with CO2 and diode lasers

EFFECTIVENESS OF LAI WITH PREVIOUSLY DETERMINED POWER SETTINGS ON ROOT DENTIN COVERED WITH SMEAR- LAYER

Group 1 as the positive control (etching) showed for all regions the highest percentage of opened tubules and received scores 5, 2a and 2b. The negative control (G2) presented a heavy smear-layer covering the entire canal and scores 1a, 2a, and 2b were attributed. *(Figures 4-6)*

The results showed, that in the coronal region *(Figure 4*), conventional chemical mechanical needle irrigation with a combination of NaOCl and EDTA (G3) was the most effective in smear-layer removal and opening of dentinal tubules. CO_2 laser with 40% power input (G5), completely sealed the root dentin with no exposure of dentinal tubules. In contrast, Er:YAG laser (G4) opened dentinal tubules partly but the smear-layer was still present. Diode lasers (G6-9) melted the dentin surface to different degrees, with only the Wiser 980nm wavelength (G9) leading to the opening of some dentinal tubules.

In the middle root third (see Figure 5), conventional syringe irrigation with NaOCl and EDTA (G3) still led to the largest root surfaces with opened dentin tubules. CO_2 laser and diode lasers (G5-9) in water led also to a certain degree of opening of tubule entrances with a similar amount of melting observed for these groups. Er:YAG laser (G4) left large areas covered with smear-layer and was not differences to the negative control with smear-layer (G2).

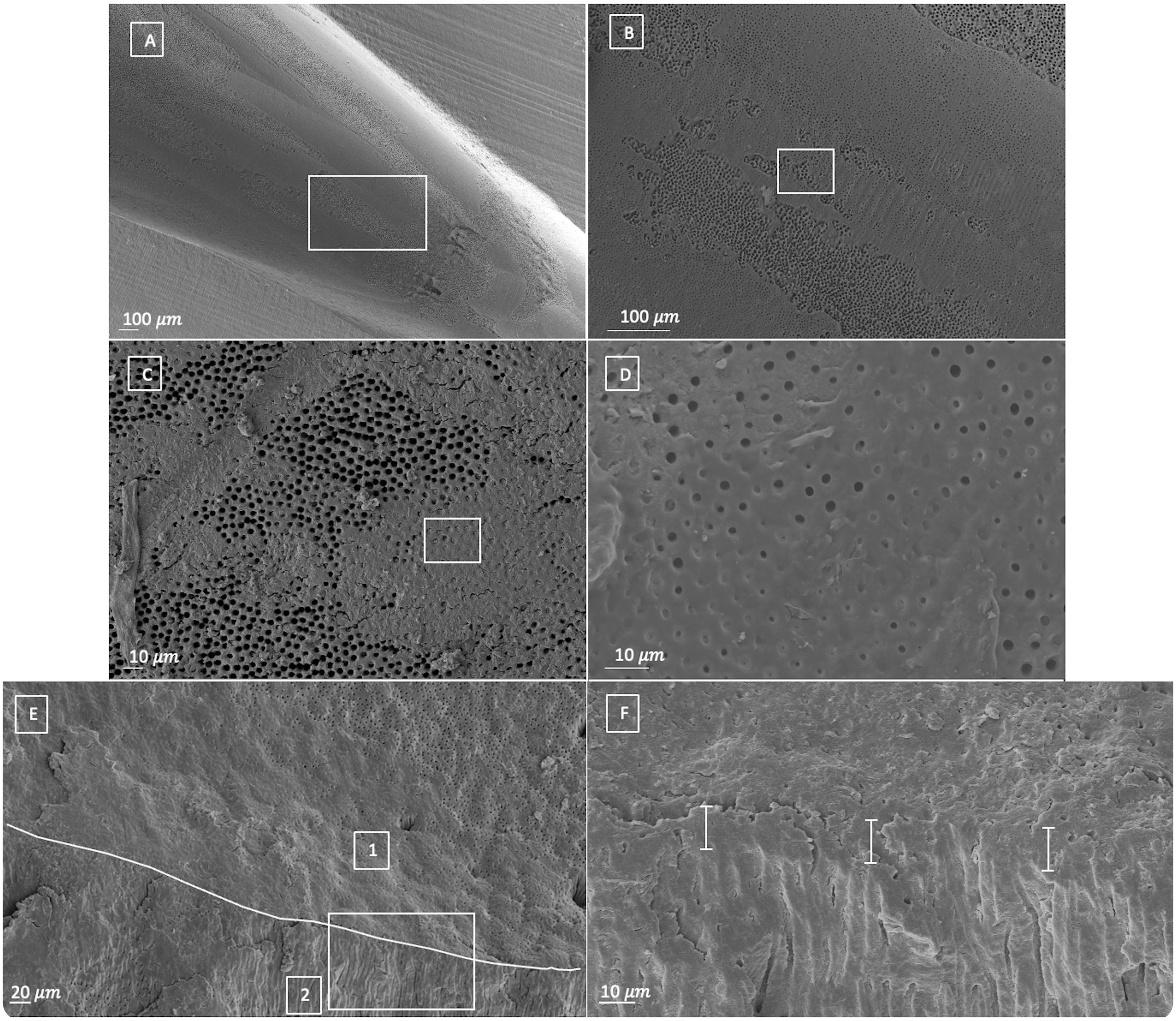

Figure 3: SEM photos of root dentin after LAI with 9300 CO_2 laser with 40% in water. A: overview of the middle root third X 52, B, C, D close ups at a magnification of X150, X500 and X1000. E: overview of fractured pre-etched root dentin in the middle root third X 200. 1: inside of main root canal, 2: fracture surface exposing dentin tubules length. F: close up of fracture at a magnification of X750. Tubules entrances melted at a depth of 8-12 μm marked with white lines.

In the apical root third (*Figure 6*) CO_2 laser (G5) led to larger regions of opened dentinal tubules than conventional needle irrigation with NaOCl and EDTA (G3) and impacted the whole region either with opening or sealing of dentinal tubules. Er:YAG (G4) and negative control (G2) were similar and diode lasers all melted the surfaces to a certain degree except for G6, in which the smear-layer was less altered.

Concerning the evaluators' scores, no difference was detected among the evaluators except for group G5, for which evaluator 3 gave lower scores

DISCUSSION

This study investigated the physical and mechanical effects of laser-activated pure water irrigation using a 9300 nm CO_2 and diode lasers with wavelengths of 455 nm, 808 nm, 970 nm and 980 nm on root canal dentin covered with smear-layer in comparison to Er:YAG laser and positive and negative controls as well as conventional needle irrigation with NaOCl and EDTA.

The authors aimed to clarify the question concerning the synergistic effects of the irrigant's chemical and mechanical action in LAI. Published literature agree, that LAI improves the cleaning effectiveness in root canal systems. However, the exact role of lasers stays unclear. In this study, we focus solely on the mechanical effect by replacing chemical irrigation with pure water.

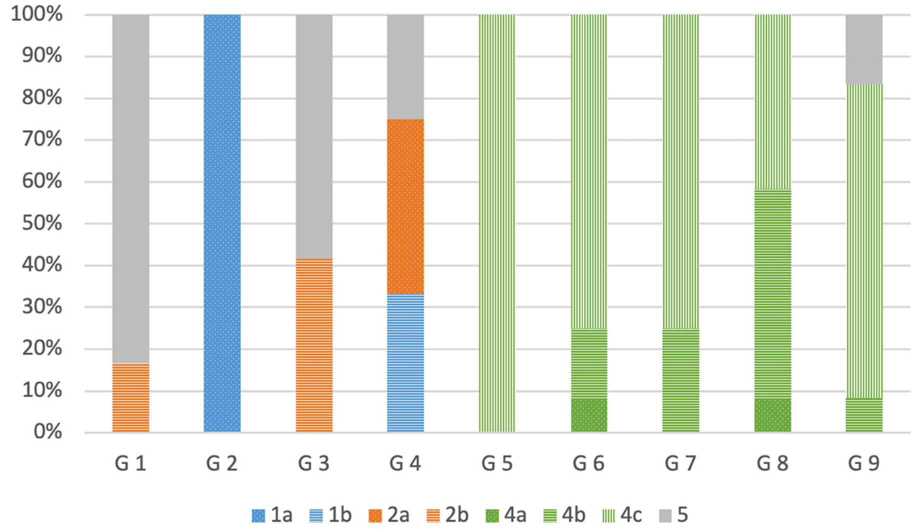

Figure 4: Score in coronal root thirds: dots represent score a, horizontal lines represent score b and vertical lines score c; G1 with score 5 and 2b; G2 with score 1a, G3 with score 5 and 2b, G4 with scores 5, 2a and 1b, G5 with score 4c, G6 with score 4a, 4b and 4c, G7 with score 4b and 4c, G8 with score 4a, 4b and 4c, G9 with score 5, 4b and 4c.

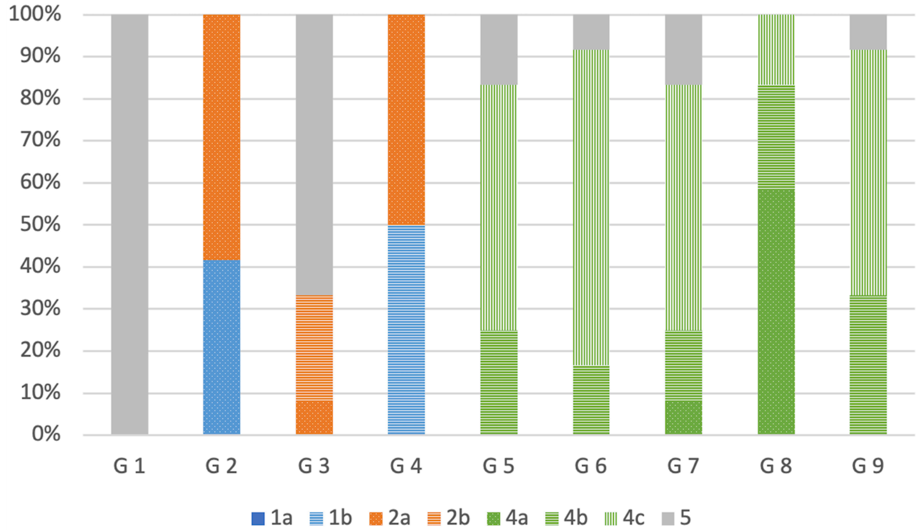

Figure 5: Score in middle root thirds: dots score a, horizontal lines score b and vertical lines score c; G1 with score 5; G2 with score 1a and 2a, G3 with score 5, 2a and 2b, G4 with scores 2a and 1b, G5 with score 5, 4b and 4c, G6 with score 5, 4b and 4c, G7 with score 5, 4b and 4c, G8 with score 4a, 4b and 4c, G9 with score 5, 4b and 4c.

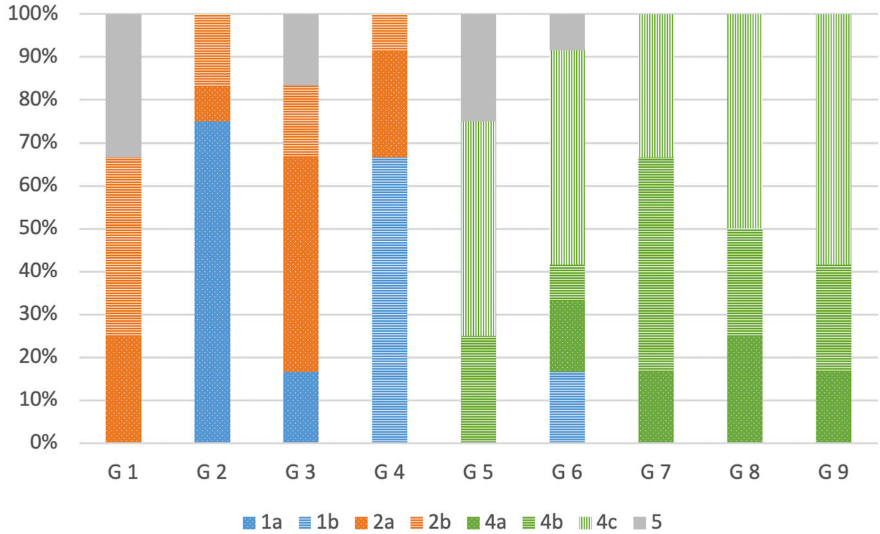

Figure 6: Score in apical root thirds: dots score a, horizontal lines score b and vertical lines score c; G1 with score 5, 2a and 2b; G2 with score 1a, 2a and 2b, G3 with score 5, 1a, 2a and 2b, G4 with scores 1b, 2a and 2b, G5 with score 5, 4b and 4c, G6 with score 5, 1b, 4a, 4b and 4c, G7 with score 4a, 4b and 4c, G8 with score 4a, 4b and 4c, G9 with score 4a, 4b and 4c.

Surprisingly, the study found that the effects of LAI led not only to the cleaning of dentinal tubule entrances from smear-layer and consequent exposition of the tubules entrances but also to melting of the root canal walls and sealing of dentinal tubules entrances with recrystallized dental material. These effects seemed to depend on the laser wavelength and laser power parameters.

Against our expectations, LAI with Er:YAG lasers did not lead to homogeneously opened dentinal tubules. Only the coronal part showed improved cleaning compared to the negative control group (G2). In this context, it should be mentioned that the number and anatomy of dentinal tubules varies among the root canal with orifices larger and denser in the coronal and middle thirds compared to the apical third.[33] However, this doesn't justify the residual smear-layer and debris in all root thirds; this finding has also been confirmed by previous studies.[17,25,26,34-38]

Based on the findings of this study, the first null hypothesis that LAI with Er:YAG lasers would be as effective as conventional chemical-mechanical irrigation in removing the smear-layer was rejected.

This finding is contradicting other published results. Studies investigating the mechanical possibilities of LAI to remove artificial debris placed in a groove in the apical portion of a root, showed very promising results of the erbium laser groups in comparison to conventional syringe irrigation with diverse chemical irrigants.[39-43]

An explication for these differences could be the fact, that smear-layer might be more difficult to detach from dentinal walls than the bigger particles of loosely placed debris, adding to that the additional chemical action of the irrigants as NaOCl or EDTA used in the cited studies. Other factors to consider are differences in applied power parameters, tip morphologies, and tip positions between the studies. All these variables make the direct comparison difficult.

Contrarily to the Er:YAG laser group, we found that the CO_2 laser at medium power parameters caused clear alterations of the smear-layer over the entire root length.

As described in studies on the ablation of dentin with the CO_2 laser,[44-46] we expected a smear-layer-free uneven surface with opened dentinal tubules, that might only be partly occluded by melted and recrystallized dental material. Depending on the laser power parameters, we found distinct large smooth areas with homogeneously melted and closed dentin tubules entrances. We therefore had to reject the second null hypothesis stating that Er:YAG and CO_2 laser equally clear dentin walls from the smear-layer.

Diode laser application lead basically to similar phenomena as the CO_2 laser but the intensity varied depending on the power parameter. There were parts observed with a completely untouched smear-layer. This is why we could reject the third null hypothesis stating that diode lasers have the same impact on root canal dentin as the other lasers.

For both, CO_2 and diode lasers, the size of the melted areas increased depending on the laser power parameter. It seemed, that the laser energy was not distributed homogeneously within the water on the canal walls. The flat cylindrical CO_2 laser tip, which was located in the pulpal chamber while activation, might direct its energy output relatively straight apically and -dependent on the laser tip orientation- also against the root canal walls. We might suppose, that the energy distribution into the liquid could be improved with modified tips, that distribute the energy more laterally.[47]

In contrast to tips of Er:YAG and CO_2 lasers, that were only introduced into the pulpal chamber but not into the root canal, diode laser tips were inserted deeply into the root canals (9 mm). Similar to the observations with the CO_2 laser we saw lines of melting. In some other parts (independent of the root third) we found cleaned tubules. We speculate, that in the "cleaned" regions the energy was just enough to induce streaming, which was strong enough to detach the smear-layer but as the laser tip was not close to the canal wall, the energy was not sufficient to melt the dentin surface.

The literature considers melting patterns as adverse effects of the lasers and claims that, high temperatures- necessary for melting- might negatively impact the tooth surrounding structures like the periodontal ligament.[48] In unpublished data from our laboratory, we could see that the temperature of the irrigation liquid increases with the 9300 nm CO_2 laser due to laser activation maximal over 23°C. Contrarily to CO_2 and Er:YAG laser, the diode laser light is basically not absorbed in water nor in hydroxyapatite but transmitted into deeper tooth layers, potentially leading to heating of the external root surface.[45,49]

However, with a black coating of the laser tip, it is possible to use the laser as a heat source and to introduce cavitation with less power input. In another unpublished work from our laboratory, we observed that power parameters > 320 mW lead to an increase of the intracanal temperature of the liquid over 30°C and possible negative alterations of the plastic model.

In this study, these laser parameters (> 320 mW) lead to charring of the dentin in the root main canal and increased external root surface temperatures (unpublished data). This could be considered an important hint for the clinical application of lasers. Laser power parameters should be as low as possible to prevent thermal injury to the periodontal ligament, which might result in root resorption, ankylosis or peri radicular necrosis.[48] Some publications go even further and conclude diode lasers to not be efficient and safe for irrigant activation as they apply high energies.[49,50]

The main issue of pulp space infection control lies in the complexity of the dentin tissue itself.[51] Endodontic treatments aim to decrease the number of bacteria within the tissues with disinfection and additional sealing of the dentin aiming to hinder bacteria colonization.

A proper seal fills not only the porosities but cuts off the remaining bacteria in deep dentin layers from nutrition supply.[52] From that point of view it could be very advantageous to melt and "naturally" obstruct dentin tubules entrances in order to replace or supplement traditionally applied sealers, that were seen to leak and degrade with time.[52]

The melted dentin due to low power parameters seemed to seal tightly the superficial 10 µm of the root canal wall. With the potential of a stable and tight seal using this technique, it might be possible to improve endodontic infection control and potentially long-term success rates.

It would be interesting to verify the results of this paper in an experimental set-up closer to the clinical situation. It might be, that the streaming properties in the roots were altered due to the fact, that they were cut and reassembled prior to use. Furthermore, the surrounding structures such as periodontal ligament, bone and different temperatures of the tissues might influence the results.

Finally, it is not clear, to which extent the liquid penetrated into the dentin. Further research should focus both on the penetration capacity of laser activated irritants into the dentin to investigate their potential to disinfect deep dentin layers and on the properties of "Laser sealed" root walls.

CONCLUSION

Based on the findings and within the limitations of this study, it can be concluded, that the chemical effect of conventional needle irrigation with NaOCl and EDTA is capable of effectively removing the smear-layer from coronal and middle root parts. Er:YAG laser activation of ultra-pure water cleaned partly the coronal parts from the smear-layer. Laser-activated irrigation with 9300 nm CO_2 and 455 nm, 808 nm, 970 and 980 nm diode laser lead over the whole root length either to cleaning with opening of the dentinal tubules or to melting of the dentin. CO_2 and diode lasers opened dentinal tubules until a certain laser power input, after that, it melted the superficial layer of dentin and sealed the dentinal tubules with recrystallized material.

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