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ORIGINAL ARTICLE

Rationale for using a double-wavelength (940 nm + 2780 nm) laser in endodontics: literature overview and proof-of-concept

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Abstract

Aim The goal of endodontic research is to report interventions, techniques or protocols that are most likely to deliver the outcomes that are of most interest to both clinicians and patients. The development of a double-wavelength laser delivered concomitantly and through the same radial firing tip (RFT) may provide a unique combination of beneficial properties that may clinically surpass all previously reported laser-assisted protocols. The aim is to present a rational literature overview that could support the adoption of simultaneous use 2780 and 940 nm wavelengths for smear layer removal and disinfection respectively.

Methods In order to provide relevant clinical data, two distinct clinical cases of relatively high endodontic complexity are reported with 1-year follow-up.

Results The results of both clinical cases show the immediate remission of symptoms, absence of clinical complications and complete radiographic healing.

Conlusions Together with the available amount of literature that could support the effectiveness of these two wavelengths to remove SL and to achieve deep dentin disinfection, it is possible to expect that this innovative combination of lasers delivered by RFT may be of high clinical relevance in the near future.

Keywords Er,Cr:YSGG laser · 940 nm diode · Double-wavelength · Endodontic outcome · Root canal treatment

Introduction

The success of endodontic therapy is found to be dependent on the ability to clean and disinfect the complex root canal system effectively [1].

However, the intricate anatomy of the root canal system, the microorganisms' invasion of dentinal tubules and the smear layer that is produced during instrumentation can be considered major obstacles for complete elimination of bacteria. The smear layer (SL) contains inorganic and organic substances, including microorganisms and remnants of necrotic debris [2–4] or providing itself a reservoir of irritants [5, 6].

Chemical irrigants such as sodium hypochlorite (NaOCl), chlorhexidine (CHX), ethylenediaminetetraacetic acid (EDTA) and MTAD (mixture of doxycycline, citric acid, and a detergent) are often used during cleaning and shaping but none of these irrigants has the characteristics of an ideal irrigant [7].

It is well known that the root canal apical third imposes a special challenge to irrigation and the balance between safety and effectiveness in this area is of particular importance [8]. The diffusion of these irrigants through the dentin is slow and may depend on several factors (e.g., temperature, concentration). Moreover, convection mechanisms during irrigant flow deliver frictional forces between the irrigant and the root canal wall (wall shear stress). Different irrigation solutions and techniques have been tested but, so far, the clinical extent of their chemo-mechanical cleaning effects of the root canal system is still a source of debate [9].

While trying to overcome their individual limitations, several protocols propose to mix or alternate between different irrigating solutions. However, several antagonistic interactions between irrigants were to be found, including the loss of free available chlorine for NaOCl when in contact with chelants,

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which consequently reduced the tissue dissolution capability and to a lesser extent antimicrobial activities. When used in combination, both CHX–EDTA and CHX–NaOCl cause precipitates that present detrimental consequences [10]. As a consequence, sterile water or saline are advocated to neutralize such interactions [8].

Despite NaOCl and CHX generally exhibiting good bactericidal properties [11, 12], calcium hydroxide (CH) is often preconized as an additional inter-appointment canal medication to overcome persistent infections. However, current clinical evidences are not able to support that multiple appointment treatments concomitant with the use of CH could provide better endodontic outcomes [13–15]. Moreover, it was demonstrated that even using a laser-assisted technique, no technique or irrigation regimen was able to effectively remove CH from the root canal irregularities [16].

Clinical data regarding both NaOCl and CHX for root canal disinfection is still conflicting and current clinical evidences are still not able to support any individual irrigation strategy. Thus, the overall available evidence on this topic is scarce and often fails to report potentially patient-relevant outcomes or even reliable guidelines for treating apical periodontitis [12, 17, 18].

Lasers have long been presented as promising alternatives to conventional chemical irrigation procedures in endodontics [19, 20]. However, the biophysical properties of each wavelength are essential to determine their possible applications/limitations and to understand how they can beneficially be used in combination.

Generally, mid-infrared erbium lasers operating at wavelengths of 2780 or 2940 nm demonstrate a high absorption coefficient for both water/aqueous solutions and hydroxyapatite whereas in the near infrared range diode lasers (810, 940, and 980 nm) are mostly absorbed by haemoglobin and melanin [21–24].

As each laser wavelength has a specific absorption coefficient for every tissue [25], their role in endodontics should be focused in two main goals: (1) debris and SL removal and (2) bacterial eradication from the root canal system and within deep dentin layers.

The 940-nm diode laser

Near-infrared lasers (NIR; 800–980 nm) are predominantly absorbed by melanin and haemoglobin, presenting high transmission through water [26]. Their high transmission into water allows near-infrared lasers to penetrate deep into dentine and interact with the bacterial cell walls. Apart of bacterial wall pigmentation, their sensitivity to short periods of temperature increments was considered crucial as regards to their survival [27].

As endodontic pathogens present pigments such as melanin in their bacterial membranes, diode lasers have been demonstrated great bactericidal ability by directly interacting with bacterial pigmented membranes [28–30] or even with the bacterial microenvironment, most likely in the form of heat [31].

The 810 nm and 940 m lasers present similar low absorption coefficients in water ($\mu_a = 0.04–0.05\ cm^{-1}$) whereas the 980-nm diode laser presents a slight absorption coefficient peak in water ($\mu_a = 0.25\ cm^{-1}$) [22]. Knowing that the root canal dentin presents high volume of water content within its molecular structure, such water peak absorption constrains 980-nm dentine penetration when compared with the other two NIR wavelengths (810 and 940 nm). Consequently, having lower absorption coefficients in water, it should be expected that both 810 and 940 nm lasers could present better biophysical behaviour in terms of dentine penetration and deep disinfection in detriment of the 980 nm laser [22, 32, 33].

Based on the same biophysical properties—despite questionable conflicting findings in literature [34–37]—it cannot not be expected that any diode laser could effectively remove smear layer and expose dentinal tubules without exciding the dentin temperature threshold [36, 38–41]. In literature, the effects of NIR lasers on SL removal are highly inconsistent and often found to be highly dependant on the final irrigation regimen [42–45].

It cannot be also expected near-infrared lasers to activate irrigants such as NaOCl, citric acid or EDTA as their absorption coefficients in such solutions range only from $\mu_a = 0.05–0.25\ cm^{-1}$ [22] and an average penetration into intra-canal irrigants between 4 and 20 cm. Therefore, cavitation effects using these wavelengths should not be expected. As a consequence, the use of a any diode laser as a single wavelength for endodontic treatments often fail to show any beneficial effects on adhesion of endodontic sealers to the root surface nor to reduce apical leakage [36, 37, 46–49]. Moreover, only output powers up to 1 W in continuous wave (CW) have shown to have no impact to the dentine structure of the main canal walls [50].

Despite inconclusive findings regarding SL removal properties, diode lasers have long been proposed as an effective strategy to disinfect the root canal system [38], with the additional advantage that unwanted temperature rise was found to be less than with Nd:YAG laser [51].

Several reports can attest the safeness of NIR lasers regarding the minimal increase of intra-canal temperature and their effects on surrounding periodontal structures [52]. However, to totally overcome any possibility of hazardous temperature increment and to cover the maximum area for bactericidal purposes, the ideal protocol for using diode lasers should include circular movements while withdrawing the fibre from the apex to coronal direction [38–41, 50, 53–56]. Despite not being mandatory, cooling with irrigation between irradiations was also found to be more effective than the passive cooling during resting time [57].

As diode lasers are characterized to have low absorption in dentin, their biggest advantage relies on how they can be highly effective for deep root canal decontamination. As NIR light is able to penetrate deep into dentinal tubules, bacterial eradication has been demonstrated to be significant up to 1000 μm [32, 58–62]. In addition, it has recently been shown that intra-canal disinfection with a 940-nm laser may have a positive bactericidal effect on bacteria present beyond the apex [63].

Thus, despite several bias mostly related to the methods and protocols adopted, there is a substantial amount of literature that is able to support the use of both 810 and 940 nm lasers with or without the adjunctive use of irrigants to assist and improve root canal disinfection [33, 40, 41, 54, 58, 62, 64–69].

The 2780-nm Er,Cr:YSGG laser

The rationale for using erbium lasers in endodontics may be briefly described as (1) the ability of infrared light to interact with aqueous solutions and produce cavitation effects capable to remove smear layer, dentinal debris and filling materials from the root canal walls [70–73] and (2) the ability of infrared light to propagate into the dentinal tubules, achieving significant bactericidal effects deeper than conventional chemical solutions [30, 74].

Since 1999, the 2780-nm Er,Cr:YSGG laser has been reported as an effective method for smear layer and debris removal [75]. Then, in the early 2000s further investigations have confirmed its potential for such application and found the relevance of water to mediate the SL ablation [76–81]. The laser-water-mediated cavitation (expansion and implosion of vapour bubbles with secondary cavitation effects that induced shear stress forces towards the main root canal) was in 2006 described as the mechanism responsible for such effective results [82].

In comparison with EDTA irrigation, hand activation or even ultrasonic-activated irrigation, the cavitation effects mediated by the Er,Cr:YSGG laser have been consistently providing superior SL removal effectiveness [70, 83–86], resulting in a significant clearance of canals/isthmuses prior obturation [87] and less microleakage following obturation [88].

As regards to the endodontic repairing materials, it was shown that the use of the Er,Cr:YSSG laser did not affect the highest adhesion properties of MTA when compared with bioactive obturation materials [89].

The bactericidal properties provided by erbium lasers are concomitantly attributed to either instant evaporation of intracellular water or bacterial dehydration [30, 90], without promoting significant or hazardous temperature changes [81]. In addition, the Er,Cr:YSGG laser has also been shown to be effective for deep root canal dentin disinfection [74, 91–93].

Being non-thermal in nature, the Er,Cr:YSGG laser irradiation has been reported to produce clinically safe temperature increments along the root canal walls [80, 81, 94–97], together with the absence of molecular dentine changes [98, 99], signs of melting or carbonization [23, 78, 81, 98].

Endodontic radial firing tips

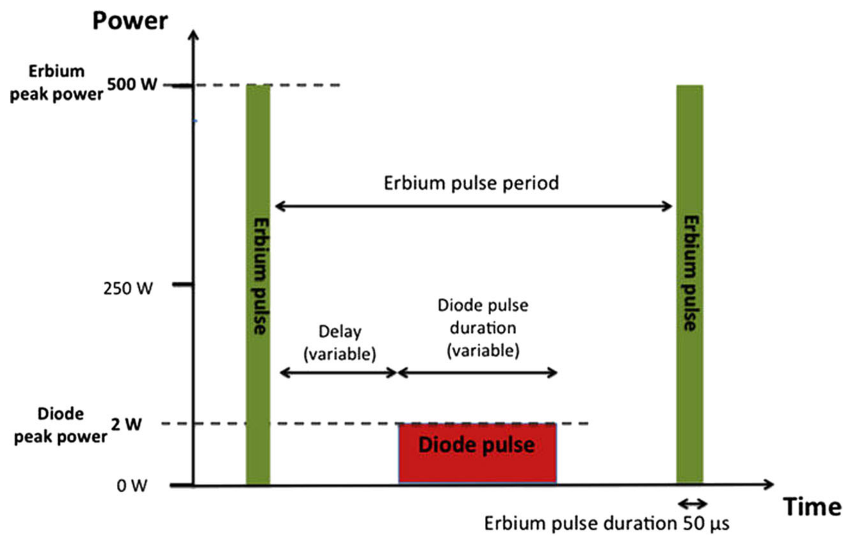
Previously, laser-assisted endodontic protocols consisted of using plain fibres (with a straightforward emission beam profile). Generally, these fibres were placed in the main canal and withdrawn from apical to coronal in a rotating motion. However, such technique is known to be technique sensitive and to produce rather inconsistent results [23, 95, 100].

Moreover, direct emission of laser irradiation from the tip of the optical fibre could result in energy transmission beyond of the apical foramen being theoretically hazardous in teeth with proximity to the mental foramen or mandibular nerve. It was reported that while using plain laser fibres in combination with irrigants, apical extrusion might also occur even under sub-ablative settings [84, 101].

Designed to overcome such limitations, radial firing tips (RFT) present a beam expansion pattern—promoted by the tip geometry—that favours a homogeneous energy distribution along the root canal wall [84, 85, 102]. In contrast with plain fibres, RFT have been shown to produce consistently relevant in vitro [102, 103] and clinical [104, 105] findings. They are known to spread its energy along to the direction of the dentinal tubules [74], to produce lower temperature increments [85], to increase cavitation effects towards the root canal walls without harming apical tissues [85, 106], to be highly efficient in bacterial and biofilm reduction [107, 108] and to allow irrigating solutions to travel apically by overcoming the airlock effect [109].

Despite the well-reported in vitro advantages of several lasers in endodontics, the Er,Cr:YSGG laser is the only one supported by clinical data demonstrating its potential benefits and long-term outcomes [104, 105, 110]. Lately, a dual-wavelength approach using two lasers in combination through the same fibre has been reported as a safe, promising concept to be incorporated for root canal therapy (Fig. 1). The rationale for adopting such technology is to incorporate the biophysical background of both Er,Cr:YSGG and 940-nm lasers. Being delivered by the same hand piece and though RFT, it may be considered a promising tool to surpass the limitations of both wavelengths, combining their beneficial properties and thus being able to provide superior outcomes [111, 112].

Fig. 1 Schematic view of the alternating pulses of Er,Cr:YSGG and 940-nm diode lasers, emitted through one radial firing tip. Adapted from [111]



As the report of clinical cases with long-term follow-ups is highly encouraged to demonstrate new treatment concepts prior the elaboration of randomized clinical trials [113], the aim of reporting the following two clinical case reports is to provide a proof-of-concept and possibly support the use of double-wavelength lasers in endodontics.

Case report #1 A 67-year-old male patient presented for consultation complaining of recurrent swelling and fistula tract related to the tooth 41. The patient's medical history was not contributory. After performing clinical and radiographic examinations, the diagnosis was compatible with root canal necrosis and asymptomatic apical periodontitis (AP). At the time of consultation, the tooth was slightly tender to percussion and mobility grade I (Fig. 2a, b). Periodontal probing depths were considered normal (< 3 mm).

Radiographic images were taken immediately following obturation (Fig. 3) and radiographed for control after 6 (Fig. 4) and 12 (Fig. 5) months.

Case report #2 A 47-year-old female patient presented for consultation complaining of increasing persistent pain related to tooth 47. The tooth was supporting a metallic-ceramic bridge supporting the importance of performing a successful root canal treatment. The patient's medical history was not contributory. After performing clinical and radiographic examinations, the diagnosis was compatible with root canal necrosis and symptomatic AP. At the time of consultation, the patient was using anti-inflammatory medication regularly but the tooth was still tender to percussion, having no mobility (Fig. 6). Periodontal probing depths were considered normal (< 3 mm). The C-shape configuration of the root canal system could be confirmed under the microscope (Fig. 7).

Radiographic images were taken immediately following obturation (Fig. 8) and controlled after 6 (Fig. 9) and 12 months (Figs. 10 and 11).

Treatment protocol

Treatment options were discussed, and the required consent obtained (Helsinki Declaration, revised in Edinburgh (2000)). No financial incentive was offered (i.e. patients were responsible for the usual root canal treatment fee).

Under local anaesthesia (2% lidocaíne with 1:100,000 epinephrine (Scandonest, Saint Maur des Fossés, France)) and rubber dam isolation (Hygenic Non-Latex Rubber Dam, Coltène/Whaledent, Germany), an access cavity was prepared with a high-speed carbide bur (SS White, Lakewood, USA). The working length (WL) was electronically established

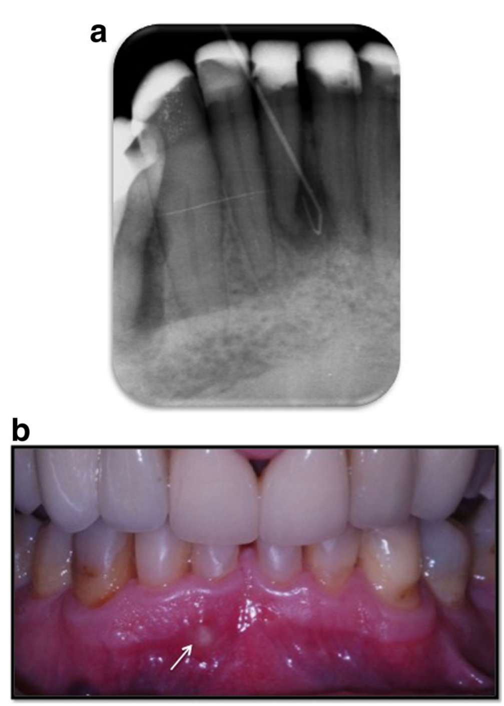


Fig. 2 **a**, **b** Case #1 initial radiograph and clinical picture of the tooth #41 together with guta percha indicating the presence of the fistula tract and AP

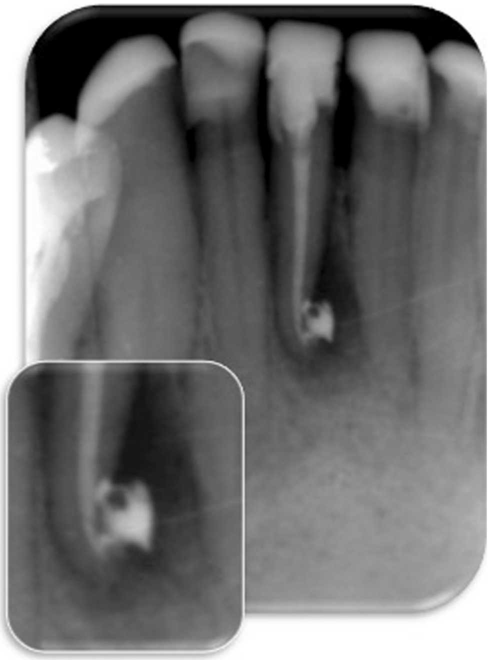


Fig. 3 Case #1 final radiograph following the completion of the double-wavelength laser-assisted treatment. To be noticed is the apical delta completely debrided and sealed

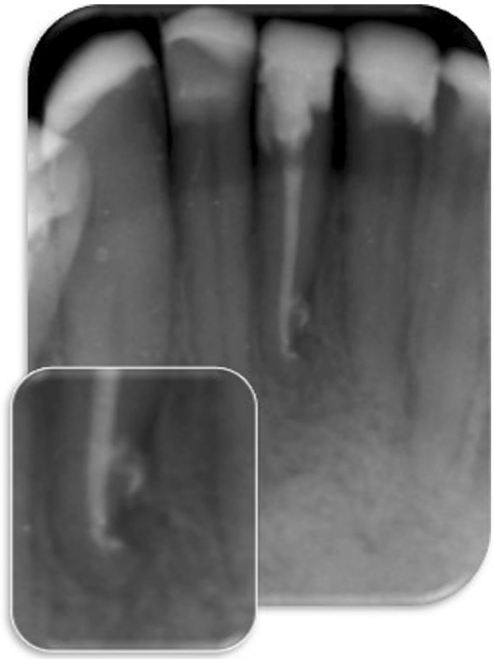


Fig. 5 Case #1 radiographic assessment with a 12-month follow up. To be noticed is the complete regression of the AP and re-establishment of the periodontal structures

(Root Zx, Morita, Japan) as 1 mm short of the biological apex of the root and confirmed by radiography. Patency was confirmed with an ISO#15 K-file, and root canal preparation was performed using the Protaper Next system (Dentsply-Maillefer, Ballaigues-Switzerland) up to an X3 (#30.07) instrument for each canal. Syringe root canal irrigation (Monoject 27G, Kendall-Covidien, USA) was performed with 3 mL of sterile saline solution between each file.

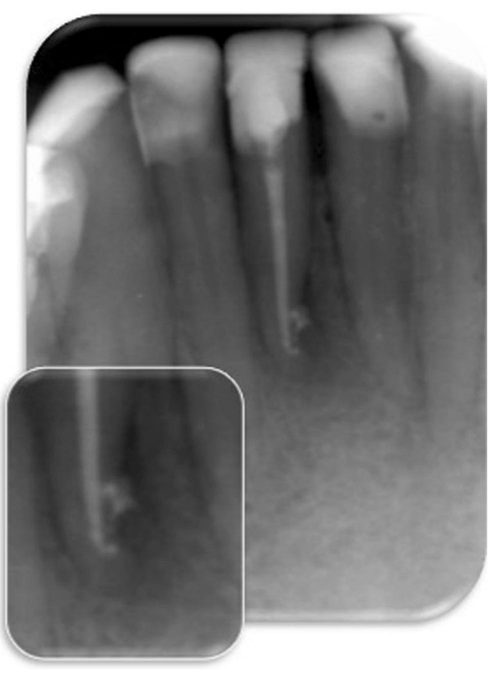


Fig. 4 Case #1 radiographic assessment with a 6-month follow-up

No chemical irrigants or inter-appointment dressings were used. For smear layer removal and root canal disinfection, a double-wavelength protocol was adopted.

Following root canal preparation, each canal was filled with distilled water and laser irradiation was concomitantly performed with the 2780-nm Er,Cr:YSGG laser and 940-nm diode laser (Biolase Technology, Irvine, CA, USA). While using a 270-μm Radial Firing Tip (RFT2, Biolase Technology; calibration factor of 0.55), the Er,Cr:YSGG laser was used with panel settings of 1.25 W, 50 Hz (25 mJ), 60 μs pulse 80% water and 30% air, while the 940-nm diode laser was operating at 1 W, continuous wave (CW).

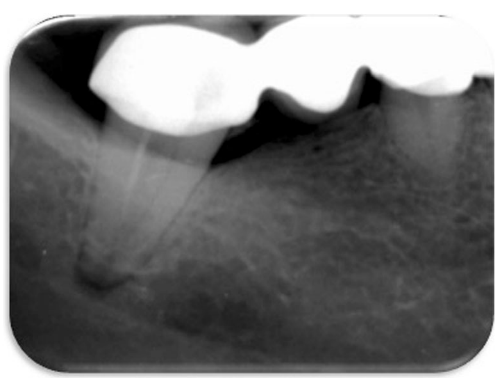


Fig. 6 Case #2 initial radiograph of the tooth #47 demonstrating the absence of apical constriction due to inflammatory resorption, the AP and the proximity to the mandibular nerve

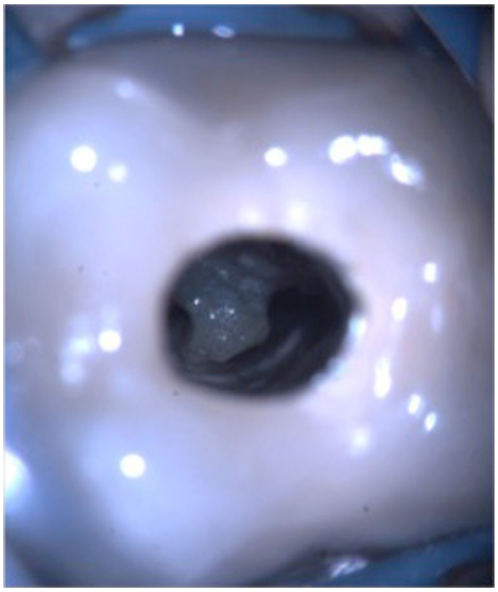


Fig. 7 Case #2 picture taken under operating microscope at 12.5X magnification (ZeissPico, Switzerland) demonstrating the C-shape configuration of the root canal system

The tip was placed up to the working length and irradiation was performed, approximately, at the speed of 2 mm/s until it reached the most coronal part of the canal. The irradiation procedure was repeated four times with approximately 15 s between each irradiation. Afterward, a sterile cotton pellet was placed in the pulp chamber, and the access cavity was sealed with glass ionomer restorative material (KETAC Molar AplicapTM, 3M ESPE, USA).

At the second appointment (after 2 weeks), there were in both cases negative histories on questioning to pain. Moreover, tenderness to percussion (and fistula tract in case #1) has disappeared completely.

Under local anaesthesia and rubber dam isolation, the canal was re-accessed. The main canals were filled with distilled water and laser irradiation was performed using the double-wavelength protocol identical to the first appointment. After irradiation, the canal was dried with isopropyl alcohol and sterile paper points while checking for the absence of any suppuration or exudate.

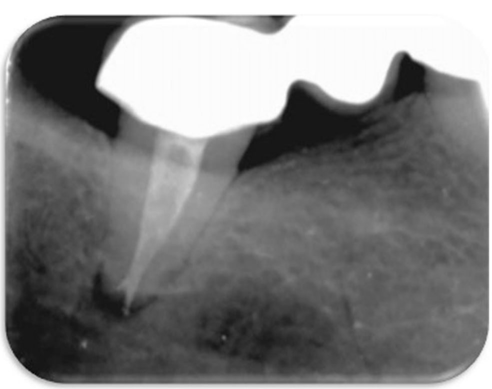


Fig. 8 Case #2 final radiograph following the completion of the double-wavelength laser-assisted treatment. To be noticed are the isthmuses between the two main canals and the apical delta completely debrided and sealed

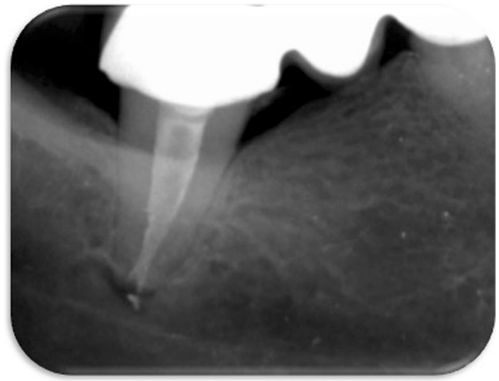


Fig. 9 Case #2 radiographic assessment with a 6-month follow-up

Filling was performed using the continuous wave of condensation technique (ElementsTM, Kerr Dental, USA) with an X3 (#30.07) auto-fit gutta-percha cone (Dentsply-Maillefer, Ballaigues-Switzerland), and a resin-based endodontic sealer (Topseal, Dentsply-Maillefer) [114].

Restoration of the access cavities was performed using Ionoseal (VOCO GmbH, Germany), SureFil SDR (Dentsply, USA), and composite (Filtek, 3M ESPE, USA).

Results

In case #1, immediately after obturation, it could also be noticed that the presence of an apical delta, including lateral canals at the apical third, were completely cleaned and obturated (Fig. 3).

As regards to case #2, the presence of a C-shape canal connecting the two main canals could be completely debrided

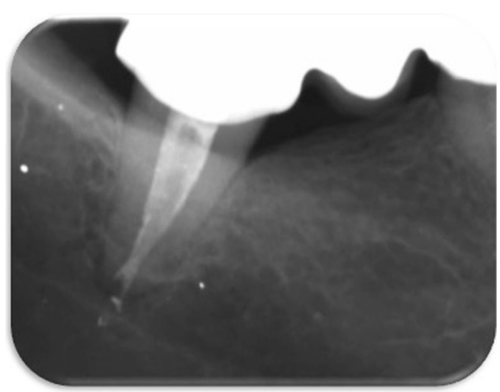


Fig. 10 Case #2 radiographic assessment with a 12-month follow-up. To be noticed the complete regression of the AP and re-establishment of the bone structure around the mandibular nerve

Fig. 11 Case #2 clinical picture demonstrating the presence of regular occlusal load and good periodontal condition at 12 months

and the connecting isthmuses were successfully sealed (Figs. 7 and 8). Although with the absence of an apical constriction (such apical configuration could be a possible factor for any extrusion of irrigants and iatrogenic accidents), the apical third was effectively cleaned and completely sealed. To be noticed, the proximity to the mandibular nerve could have represented an additional challenge in case of performing traditional irrigation regimens. The tooth remained in function during the treatment and follow-up period (Fig. 11).

In both clinical cases, there was an absolute remission of symptoms after the first appointment. Continuous radiographic regression of the AP could be observed following the completion of the double-wavelength laser-assisted treatment and throughout the 12-month follow-up period. Moreover, after 12 months, there were evident radiographic signs of positive changes in bone density (trabecular reformation followed by lamina dura formation) (Figs. 5 and 10). Clinical signs and symptoms disappeared completely and a healthy periodontal status could be confirmed, indicating the successful endodontic outcomes in both cases.

Discussion

One of the most important factors affecting the prognosis of an endodontic treatment is the preoperative presence of AP due to the lower success rates when compared with normal teeth radiographic appearance [115, 116]. Due to the fact there are still missing clinical guidelines for treating teeth with AP, further research is continuously demanded to highlight which are the protocol-related factors that can interfere with endodontic outcomes [18].

It was shown that there are no significant differences in healing of AP when comparing obturated and non-obturated teeth after instrumentation, and it appears that the quality of root canal filling does not directly interfere with endodontic outcomes. Hence, the success of an endodontic treatment ultimately depends on the elimination of the microorganism, host response and coronal seal of root canals [117, 118]. Other possible predictive factors such as age, gender, tooth type, root-end filling material and magnification type had no significant effect on the proportion of success [119].

Both case reports presented a follow-up period of 12 months following the completion of the endodontic therapy. After 1 year of follow-up, the (re)emergence of apical periodontitis may not be directly related to the endodontic treatment itself but to extrinsic factors such as quality of obturation or coronal seal [120]. Therefore, the adoption of 12 months as end-point to establish de course of an endodontic outcome is highly recommended.

For the above-mentioned clinical cases, there were no medication prescriptions during or following the treatment. Antibiotics are currently overprescribed for the management of endodontic infections such as symptomatic irreversible pulpitis, necrotic pulps and localized acute apical abscesses. However, it is highly recommended that the primary aim while treating teeth with AP and localized swelling or pain is to achieve drainage and disinfection without additional use of antibiotics [121, 122]. Despite being limited to two clinical cases, laser-assisted endodontic treatments may support and corroborate this position statement.

Several reports can be found in literature using distinct laser wavelengths for endodontic purposes. In their vast majority, the emission pattern of laser energy is directed along to the main root canal due to the bare-end configuration of endodontic fibres. To overcome this limitation while using straight forward emitting fibres, circular movements during irradiation are proposed by several investigations. Nevertheless, such rotational movements still do not allow to predictably obtain a uniform coverage of the entire the root canal system [100].

It was long reported that lateral emission could tri-dimensionally cover the entire root canal system and penetrate directly into distinct anatomic configurations as well as within the dentinal tubules [123]. The present report used radial firing tips that are shown to be useful in cleaning and tri-dimensionally disinfecting both intricate root canal anatomies.

In contrast with the previous reports using RFT in straight canals of the anterior teeth [104, 110], the RFT used in these two clinical cases were moved in a spiralling motion along the root canal walls. The aim was to facilitate the fibre withdrawing motion and to possibly overcome any ledging that may occur in apical thirds of curved canals. In fact, it is known that the effect of the laser may vary accordingly to different foramina sizes and dentin width [63] and these factors should be taken into high consideration while selecting an appropriate protocol for specific clinical conditions.

The two clinical cases in this report presented wide apical configurations. The apical foramen can be wide due to over instrumentation, root-end resection, incompletely formed root apex or inflammatory root resorption of endodontic origin [124]. Such apical configurations can attest the importance of adopting an alternative strategy to conventional and possibly hazardous irrigants such as NaOCl. The use of the Er,Cr:YSGG laser with low power outputs is able to drive irrigation solutions to the tip of the canal without harming apical tissues [106]. The use of Er,Cr:YSGG laser, RFT and distilled water as an irrigant surely prevents any possible iatrogenic damage. This may be of an additional importance in case of proximity of sensitive structures such as the mandibular nerve as in case #2. The fact that both patients did not have any postoperative pain might attest the safeness of the adopted protocol relatively to wide apical configurations.

Still regarding to the use of endodontic fibres, one should have taken into consideration that the power emitted on the distal end of the fibre may not be always the same as the one presented on the display due to the calibration factor of the fibre [53]. The RFT2 tips used in both clinical cases present a calibration factor of 0.55. This would mean that for 1.25 and 1 W used for Er,Cr:YSGG and diode lasers, the output powers are 0.69 and 0.55 W respectively.

In accordance to evidence-based clinical evidences, no intra-canal medication (e.g. calcium hydroxide) was placed between appointments. The clinical use of CH is controversial, but as regards to the removal of CH from the root canal walls, the Er,Cr:YSGG laser-activated irrigation may significantly be more effective than other irrigation regimens. However, no technique was able to remove the CH dressing completely [16].

To achieve predictable disinfection levels, two wavelengths were used simultaneously. Both 2780- and 940-nm lasers have been shown to be powerful tools in cleaning and disinfecting root canals. According to each wavelength, it has been demonstrated that dentinal tubules may act as optic channels, redirecting and transmitting laser light deeply in multiple directions [125]. This might be supported by the clearance consequent sealer penetration within secondary lateral canals together with the successful healing of the periapical structures in both clinical cases.

As diode lasers under 1 W do not interfere with the dentin micro-structure and that the Er,Cr:YSGG laser produces SL-free canals with open dentinal tubules, the use of resin-based sealers following laser-assisted endodontic procedures is advocated [47, 126]. In the present case report, and in similarity with the available clinical data [104, 105, 110], the use of a resin-based sealer (Topseal, Dentsply-Maillefer) has demonstrated high affinity for dentin penetration and hermetic seal.

The possibility of using two distinct lasers with two complementary effects (cavitation-induced debris and SL removal by the Er,Cr:YSGG laser and the superior dentin penetration/disinfection of the 940 nm diode) seems a very promising and logical combination. In addition, the possibility to deliver both wavelengths through the same radial firing tip guarantees the tri-dimensional coverage of the entire root canal system and allows directing both lasers into intricate root canal configurations.

In practically all levels of evidence (LOE) classification systems, randomized controlled trials (RCTs) are considered as a high LOE, as opposed to case reports and case series that are considered as a low LOE [127–130]. However, from the clinical perspective, the study design and the ensuing LOE classification as a decisive factor for the evidence appraisal can be misleading.

Traditional LOE grading systems often fail to provide any information regarding the relevance of the investigated clinical question to the practitioner's decision-making. Thus, not only the strength of the evidence should be considered but also the clinical significance and relevance of the evidence. Occasionally, an RCT may be less significant to the clinical decision-making than a case series study, i.e. when a clinician assesses the benefits and risks of a possible treatment modality [131] such as the risk represented by proximity of the mandibular nerve (case #2). Therefore, different types of questions may require different types of evidence and both significance and relevance of the evidence seems to be more intuitive and subjective [132].

As clinical significance can be defined as "the practical or applied value or importance of the effect of an intervention", treatments that produce reliable effects may be quite different in their impact on patients' function [133], the clinical significance of double-wavelengths laser-assisted endodontic treatment in terms of outcomes, safeness, time consuming, etc., may attest the importance of further report clinical cases, namely under different clinical scenarios. Hence, there is the aim to continue reporting clinically relevant data to enhance level of evidence of these promising but yet preliminary findings.

Conclusion

The goal of decision-making in healthcare is to choose the interventions that are most likely to deliver the outcomes that are of most interest to patients while preventing possible harmful outcomes [134]. With this manuscript, the aim was to demonstrate that laser-technology is in far expansion within the endodontic field and that with double-wavelength lasers, clinicians should expect to achieve highly predictable outcomes and less iatrogenic complications even in the most complicated endodontic scenarios such as in multi-rooted teeth with unfavourable anatomies, associated with AP. To provide higher level of evidence that may corroborate these preliminary clinical findings further investigations are encouraged.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent Informed consent (Helsinki Declaration, revised in Edinburgh) was obtained from all individual participants included in the study.

References

1. Schilder H (1974) Cleaning and shaping the root canal. Dent Clin N Am 18(2):269–296
2. Torabinejad M, Handysides R, Khademi AA, Bakland LK (2002) Clinical implications of the smear layer in endodontics: a review. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 94(6):658–666. https://doi.org/10.1067/moe.2002.128962
3. Pashley DH (1992) Smear layer: overview of structure and function. Proc Finn Dent Soc 88(Suppl 1):215–224
4. Moon YM, Shon WJ, Baek SH, Bae KS, Kum KY, Lee W (2010) Effect of final irrigation regimen on sealer penetration in curved root canals. J Endod 36(4):732–736. https://doi.org/10.1016/j.joen.2009.12.006
5. Pashley DH (1984) Smear layer: physiological considerations. Oper Dent Suppl 3:13–29
6. Fogel HM, Pashley DH (1990) Dentin permeability: effects of endodontic procedures on root slabs. J Endod 16(9):442–445. https://doi.org/10.1016/S0099-2399(06)81888-1
7. Ordinola-Zapata R, Bramante CM, Garcia RB, de Andrade FB, Bernardineli N, de Moraes IG, Duarte MA (2013) The antimicrobial effect of new and conventional endodontic irrigants on intra-orally infected dentin. Acta Odontol Scand 71(3–4):424–431. https://doi.org/10.3109/00016357.2012.690531
8. Haapasalo M, Shen Y, Wang Z, Gao Y (2014) Irrigation in endodontics. Br Dent J 216(6):299–303. https://doi.org/10.1038/sj.bdj.2014.204
9. van der Sluis LW (2015) Endodontics in motion: new concepts, materials and techniques 3. The role of irrigants during root canal treatment. Ned Tijdschr Tandheelkd 122(10):533–538. https://doi.org/10.5177/ntvt.2015.10.15181
10. Rossi-Fedele G, Dogramaci EJ, Guastalli AR, Steier L, de Figueiredo JA (2012) Antagonistic interactions between sodium hypochlorite, chlorhexidine, EDTA, and citric acid. J Endod 38(4):426–431. https://doi.org/10.1016/j.joen.2012.01.006
11. Mohammadi Z (2008) Sodium hypochlorite in endodontics: an update review. Int Dent J 58(6):329–341. https://doi.org/10.1111/j.1875-595X.2008.tb00354.x
12. Fedorowicz Z, Nasser M, Sequeira-Byron P, de Souza RF, Carter B, Heft M (2012) Irrigants for non-surgical root canal treatment in mature permanent teeth. Cochrane Database Syst Rev 9: CD008948
13. Paredes-Vieyra J, Enriquez FJ (2012) Success rate of single- versus two-visit root canal treatment of teeth with apical periodontitis: a randomized controlled trial. J Endod 38(9):1164–1169. https://doi.org/10.1016/j.joen.2012.05.021
14. Xavier AC, Martinho FC, Chung A, Oliveira LD, Jorge AO, Valera MC, Carvalho CA (2013) One-visit versus two-visit root canal treatment: effectiveness in the removal of endotoxins and cultivable bacteria. J Endod 39(8):959–964. https://doi.org/10.1016/j.joen.2013.04.027
15. Manfredi M, Figini L, Gagliani M, Lodi G (2016) Single versus multiple visits for endodontic treatment of permanent teeth. Cochrane Database Syst Rev 12:CD005296
16. Kustarci A, Er K, Siso SH, Aydin H, Harorli H, Arslan D, Kirmali O (2016) Efficacy of laser-activated Irrigants in calcium hydroxide removal from the artificial grooves in root canals: an ex vivo study. Photomed Laser Surg 34(5):205–210. https://doi.org/10.1089/pho.2015.3951
17. Goncalves LS, Rodrigues RC, Andrade Junior CV, Soares RG, Vettore MV (2016) The effect of sodium hypochlorite and chlorhexidine as irrigant solutions for root canal disinfection: a systematic review of clinical trials. J Endod 42(4):527–532. https://doi.org/10.1016/j.joen.2015.12.021
18. Del Fabbro M, Corbella S, Sequeira-Byron P, Tsesis I, Rosen E, Lolato A, Taschieri S (2016) Endodontic procedures for retreatment of periapical lesions. Cochrane Database Syst Rev 10:CD005511
19. Kimura Y, Wilder-Smith P, Matsumoto K (2000) Lasers in endodontics: a review. Int Endod J 33(3):173–185. https://doi.org/10.1046/j.1365-2591.2000.00280.x
20. Gutknecht N, Kaiser F, Hassan A, Lampert F (1996) Long-term clinical evaluation of endodontically treated teeth by Nd:YAG lasers. J Clin Laser Med Surg 14(1):7–11. https://doi.org/10.1089/clm.1996.14.7
21. Fried D, Featherstone JDB, Visuri SR, Seka W, Walsh JT (1996) The caries inhibition potential of Er:YAG and Er,Cr:YSGG laser radiation. SPIE Proc 2672:2673–2678
22. Meire MA, Poelman D, De Moor RJ (2014) Optical properties of root canal irrigants in the 300-3,000-nm wavelength region. Lasers Med Sci 29(5):1557–1562. https://doi.org/10.1007/s10103-013-1307-4
23. Minas NH, Gutknecht N, Lampert F (2010) In vitro investigation of intra-canal dentine-laser beam interaction aspects: II. Evaluation of ablation zone extent and morphology. Lasers Med Sci 25(6):867–872. https://doi.org/10.1007/s10103-009-0722-z
24. Mohammadi Z (2009) Laser applications in endodontics: an update review. Int Dent J 59(1):35–46
25. Cercadillo-Ibarguren I, Espana-Tost A, Arnabat-Dominguez J, Valmaseda-Castellon E, Berini-Aytes L, Gay-Escoda C (2010) Histologic evaluation of thermal damage produced on soft tissues by CO2, Er,Cr:YSGG and diode lasers. Med Oral Patol Oral Cir Bucal 15(6):e912–e918
26. Falkenstein F, Gutknecht N, Franzen R (2014) Analysis of laser transmission and thermal effects on the inner root surface during periodontal treatment with a 940-nm diode laser in an in vitro pocket model. J Biomed Opt 19(12):128002. https://doi.org/10.1117/1.JBO.19.12.128002
27. Moritz AJS, Goharkhay K, Schoop U, Kluger W, Mallinger R, Sperr W, Georgopoulos A (2000) Morphologic changes correlating to different sensitivies of Escherichia coli and Enterococcus faecails to Nd:YAG laser irradiation through dentin. Laser Surg Med 26(3):250–261. https://doi.org/10.1002/(SICI)1096-9101(2000)26:3<250::AID-LSM2>3.0.CO;2-H
28. Meral GTF, KocagoZ S, Sener C (2003) Factors affecting the antibacterial effects of Nd:YAG laser in vivo. Laser Surg Med 32(3):197–202. https://doi.org/10.1002/lsm.10128
29. Rooney JMM, Leeming J (1994) A laboratory investigation of the bactericidal effect of a Nd:YAG laser. Br Dent J 176(2):61–64. https://doi.org/10.1038/sj.bdj.4808364
30. Lopez-Jimenez L, Arnabat-Dominguez J, Vinas M, Vinuesa T (2015) Atomic force microscopy visualization of injuries in

Enterococcus faecalis surface caused by Er,Cr:YSGG and diode lasers. Med Oral Patol Oral Cir Bucal 20(1):e45–e51
31. Pirnat S, Lukac M, Ihan A (2011) Study of the direct bactericidal effect of Nd:YAG and diode laser parameters used in endodontics on pigmented and nonpigmented bacteria. Lasers Med Sci 26(6): 755–761. https://doi.org/10.1007/s10103-010-0808-7
32. Gutknecht NFR, Schippers M, Lampert F (2004) Bactericidal effect of a 980-nm diode laser in the root canal wall dentin of bovine teeth. J Clin Laser Med Surg 22(1):9–13. https://doi.org/10.1089/104454704773660912
33. Asnaashari M, Ebad LT, Shojaeian S (2016) Comparison of antibacterial effects of 810 and 980-nanometer diode lasers on Enterococcus faecalis in the root canal system—an in vitro study. Laser Ther 25(3):209–214. https://doi.org/10.5978/islsm.16-OR-17
34. Raldi DPMI, Neves AC, Habitante SM, Miyagi SS, Lage-Marques JL (2010) Attachment of cultured fibroblasts and ultrastructural analysis of simulated cervical resorptions treated with high-power lasers and MTA. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 109(2):154–161
35. Esteves-Oliveira M, de Guglielmi C, Ramalho KM, Arana-Chavez VE, de Eduardo CP (2010) Comparison of dentin root canal permeability and morphology after irradiation with Nd: YAG, Er:YAG, and diode lasers. Lasers Med Sci 25(5):755–760. https://doi.org/10.1007/s10103-010-0775-z
36. Wang XSY, Kimura Y, Kinoshita J, Ishizaki NT, Matsumoto K (2005) Effects of diode laser irradiation on smear layer removal from root canal walls and apical leakage after obturation. Photomed Laser Surg 23(6):575–581. https://doi.org/10.1089/pho.2005.23.575
37. Faria MI, Souza-Gabriel AE, Alfredo E, Messias DC, Silva-Sousa YT (2011) Apical microleakage and SEM analysis of dentin surface after 980 nm diode laser irradiation. Braz Dent J 22(5):382–387. https://doi.org/10.1590/S0103-64402011000500006
38. Moritz AGN, Goharkhay MD, Schoop U, Wernisch J, Sperr W (1997) In vitro irradiation of infected root canals with a diode laser: results of microbiologic, infrared spectrometric, and stain penetration examinations. Quintessence Int 28(3):205–209
39. da Costa Ribeiro ANG, Antoniazzi J, Moritz A, Zerzell D (2007) Effects of diode laser (810nm) irradiation on root canal walls: thermographic and morphological studies. J Endod 33(3):252–255. https://doi.org/10.1016/j.joen.2006.09.002
40. RadaelliCM ZD, Cai S, Antunes A, Gouw-Soares S (2003) Effect of a high power diode laser irradiation in root canals contaminated with Enterococcus faecalis. “In vitro” study. In: Ishikawa IFJ, Aoki A (eds) Lasers in dentistry, revolution of dental treatment in the new millennium. Elsevier Science, B.V, Amsterdam, pp 273–276
41. Kreisler MKW, Beck M, Al Haj H, Christoffers AB, Götz H, Duschner H, Jansen B, d'Hoedt B (2003) Efficacy of NaOCl/H2O2 irrigation and GaAlAs laser in decontamination of root canals in vitro. Laser Surg Med 32(3):189–196. https://doi.org/10.1002/lsm.10148
42. Marchesan MA, Brugnera-Junior A, Ozorio JE, Pecora JD, Sousa-Neto MD (2008) Effect of 980-nanometer diode laser on root canal permeability after dentin treatment with different chemical solutions. J Endod 34(6):721–724. https://doi.org/10.1016/j.joen.2008.02.020
43. Alfredo ES-GA, Silva SRC, Sousa-Neto MD, Brugnera-Junior A, Silva-Sousa YTC (2009) Morphological alterations of radicular dentine pretreated with different irrigating solutions and irradiated with 980-nm diode laser. Microsc Res Tech 72(1):22–27. https://doi.org/10.1002/jemt.20638
44. Arslan H, Ayranci LB, Karatas E, Topcuoglu HS, Yavuz MS, Kesim B (2013) Effect of agitation of EDTA with 808-nanometer diode laser on removal of smear layer. J Endod 39(12):1589–1592. https://doi.org/10.1016/j.joen.2013.07.016
45. Kocak S, Cicek E, Saglam BC, Kocak MM, Turker SA (2015) Influence of diode laser application on the efficiency of QMiX and EDTA solutions in removing smear layer. Photomed Laser Surg 33(11):564–567. https://doi.org/10.1089/pho.2015.3910
46. de Souza EB, de Amotim C, Marques JL (2006) Effect of diode laser irradiation on the apical sealing of MTA retrofills. Braz Oral Res 20(3):231–234. https://doi.org/10.1590/S1806-83242006000300009
47. Moura-Netto CPT, Davidowicz H, de Moura AA (2009) Apical leakage of three resin-based endodontic sealers after 810-nm-diode laser irradiation. Photomed Laser Surg 27(6):891–894. https://doi.org/10.1089/pho.2008.2308
48. Faria MIS-GA, Alfredo E, Messias DCF, Silva-Sousa YTC (2001) Apical microleakage and SEM analyis of dentin surface after 980 nm diode laser irradiation. Braz Dent J 22(5):382–387
49. Todea CBC, Sinescu C, Filip L, Kerezsi C, Calniceanu M, Negrutiu M, Bradu A, Hughes M (2010) En face optical coherance tomography investigation of apical microleakage after laser assisted endodontic treatment. Lasers Med Sci 25(5):629–639. https://doi.org/10.1007/s10103-009-0680-5
50. Schoop UKW, Dervisbegovic S, Goharkhay K, Wernisch J, Georgopoulos A, Sperr W, Moritz A (2006) Innovative wavelengths in endodontic treatment. Laser Surg Med 38(6):624–630. https://doi.org/10.1002/lsm.20331
51. de Moor R, Torbeyns D, Meire M (2009) Lasers in endodontics. Part 2: root canal cleanliness and modification. Endo Endodontic Pract Today 3(1):19–33
52. Saydjari Y, Kuypers T, Gutknecht N (2016) Laser application in dentistry: irradiation effects of Nd:YAG 1064 nm and diode 810 nm and 980 nm in infected root canals—a literature overview. Biomed Res Int 2016:8421656
53. Gutknecht NFR, Meister J, Vanweersch L, Mir M (2005) Temperature evolution on human teeth root surface after diode laser assisted endodontic treatment. Lasers Med Sci 20(2):99–103. https://doi.org/10.1007/s10103-005-0347-9
54. Schoop UKW, Moritz A, Nedjelik N, Georgopoulos A, Sperr W (2004) Bactericidal effect of different laser systems in the deep layers of dentin. Laser Surg Med 35(2):111–116. https://doi.org/10.1002/lsm.20026
55. Alfredo EMM, Sousa-Neto MD, Brugnera-Junior A, Silva-Sousa YTC (2008) Temperature variation at the external root surface during 980-nm diode laser irradiation in the root canal. J Dent 36(7):529–534
56. Cretella G, Lajolo C, Castagnola R, Somma F, Inchingolo M, Marigo L (2017) The effect of diode laser on planktonic Enterococcus faecalis in infected root canals in an ex vivo model. Photomed Laser Surg 35(4):190–194. https://doi.org/10.1089/pho.2016.4174
57. Hmud R, Kahler WA, Walsh LJ (2010) Temperature changes accompanying near infrared diode laser endodontic treatment of wet canals. J Endod 36(5):908–911. https://doi.org/10.1016/j.joen.2010.01.007
58. Beer F, Buchmair A, Wernisch J, Georgopoulos A, Moritz A (2012) Comparison of two diode lasers on bactericidity in root canals—an in vitro study. Lasers Med Sci 27(2):361–364. https://doi.org/10.1007/s10103-011-0884-3
59. Klinke TKW, Gutknecht N (1997) Antibacterial effects of Nd: YAG laser irradiation within root canal dentin. J Clin Laser Med Surg 15(1):29–31
60. Asnaashari M, Safavi N (2013) Disinfection of contaminated canals by different laser wavelengths, while performing root canal therapy. J Lasers Med Sci 4(1):8–16
61. de Souza EB, Cai S, Simionato MR, Lage-Marques JL (2008) High-power diode laser in the disinfection in depth of the root

canal dentin. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 106(1):e68–e72. https://doi.org/10.1016/j.tripleo.2008.02.032

62. Vatkar NA, Hegde V, Sathe S (2016) Vitality of Enterococcus faecalis inside dentinal tubules after five root canal disinfection methods. J Conserv Dent 19(5):445–449. https://doi.org/10.4103/0972-0707.190019
63. Jyotsna SV, Raju RV, Patil JP, Singh TV, Bhutani N, Kamishetty S, Ghatole K (2016) Effect of diode laser on bacteria beyond the apex in relation to the size of the apical preparation—an in-vitro study. J Clin Diagn Res 10(5):ZC63–ZC65. https://doi.org/10.7860/JCDR/2016/17759.7791
64. Kuvvetli S, Sandalli N, Topcuoglu N, Kulekci G (2009) Antibacterial efficacy of diode and Er:YAG laser irradiation in experimentally contaminated primary molar root canals. J Clin Pediatr Dent 34(1):43–48. https://doi.org/10.17796/jcpd.34.1.n4172034x4054336
65. Moritz AGN, Schoop U, Goharkhay K, Doertbudak O, Sperr W (1997) Irradiation of infected root canals with a diode laser in vivo: results of microbiological examinations. Laser Surg Med 21(3):221–226. https://doi.org/10.1002/(SICI)1096-9101(1997)21:3<221::AID-LSM1>3.0.CO;2-S
66. Gutknecht NVGD, Conrads G, Apel C, Schubert C, Lampert F (2000) Diode laser radiation and its bactericidal effect in root canal wall dentin. J Clin Laser Med Surg 18(2):57–60
67. Benedicenti SCC, Signore A, Ravera G, Angiero F (2008) Decontamination of root canals with the gallium-aluminium-arsenide laser: an in vitro study. Photomed Laser Surg 26(4):367–370. https://doi.org/10.1089/pho.2008.2158
68. Mehrvarzfar PSM, Asatourian A, Fekrazad R, Karamifar K, Eslami G, Dadresanfar B (2011) Additive effect of a diode laser on the antibacterial activity of 2,5% NaOCl, 2% CHX and MTAD against Enterococcus faecalis contaminating root canals: an in vitro study. J Oral Sci 53(3):355–360. https://doi.org/10.2334/josnusd.53.355
69. Asnaashari M, Godiny M, Azari-Marhabi S, Tabatabaei FS, Barati M (2016) Comparison of the antibacterial effect of 810 nm diode laser and photodynamic therapy in reducing the microbial flora of root canal in endodontic retreatment in patients with periradicular lesions. J Lasers Med Sci 7(2):99–104. https://doi.org/10.15171/jlms.2016.17
70. De Moor RJ, Blanken J, Meire M, Verdaasdonk R (2009) Laser induced explosive vapor and cavitation resulting in effective irrigation of the root canal. Part 2: evaluation of the efficacy. Lasers Surg Med 41(7):520–523. https://doi.org/10.1002/lsm.20797
71. Matsumoto H, Yoshimine Y, Akamine A (2011) Visualization of irrigant flow and cavitation induced by Er:YAG laser within a root canal model. J Endod 37(6):839–843. https://doi.org/10.1016/j.joen.2011.02.035
72. Keles A, Arslan H, Kamalak A, Akcay M, Sousa-Neto MD, Versiani MA (2014) Removal of filling materials from oval-shaped canals using laser irradiation: a micro-computed tomographic study. J Endod 41(2):219–224. https://doi.org/10.1016/j.joen.2014.09.026
73. Jiang S, Zou T, Li D, Chang JW, Huang X, Zhang C (2016) Effectiveness of sonic, ultrasonic, and photon-induced photoacoustic streaming activation of NaOCl on filling material removal following retreatment in oval canal anatomy. Photomed Laser Surg 34(1):3–10. https://doi.org/10.1089/pho.2015.3937
74. Franzen R, Esteves-Oliveira M, Meister J, Wallerang A, Vanweersch L, Lampert F, Gutknecht N (2009) Decontamination of deep dentin by means of erbium, chromium:yttrium-scandium-gallium-garnet laser irradiation. Lasers Med Sci 24(1):75–80. https://doi.org/10.1007/s10103-007-0522-2
75. Hossain M, Nakamura Y, Yamada Y, Kimura Y, Matsumoto N, Matsumoto K (1999) Effects of Er,Cr:YSGG laser irradiation in human enamel and dentin: ablation and morphological studies. J Clin Laser Med Surg 17(4):155–159. https://doi.org/10.1089/clm.1999.17.155
76. DG Y, Kimura Y, Kinoshita J, Matsumoto K (2000) Morphological and atomic analytical studies on enamel and dentin irradiated by an erbium, chromium:YSGG laser. J Clin Laser Med Surg 18(3):139–143
77. Hossain M, Nakamura Y, Yamada Y, Suzuki N, Murakami Y, Matsumoto K (2001) Analysis of surface roughness of enamel and dentin after Er,Cr:YSGG laser irradiation. J Clin Laser Med Surg 19(6):297–303. https://doi.org/10.1089/104454701753342749
78. Ishizaki NT, Matsumoto K, Kimura Y, Wang X, Kinoshita J, Okano SM, Jayawardena JA (2004) Thermographical and morphological studies of Er,Cr:YSGG laser irradiation on root canal walls. Photomed Laser Surg 22(4):291–297. https://doi.org/10.1089/pho.2004.22.291
79. Kimura Y, DG Y, Kinoshita J, Hossain M, Yokoyama K, Murakami Y, Nomura K, Takamura R, Matsumoto K (2001) Effects of erbium, chromium:YSGG laser irradiation on root surface: morphological and atomic analytical studies. J Clin Laser Med Surg 19(2):69–72. https://doi.org/10.1089/104454701750285386
80. Yamazaki R, Goya C, Yu DG, Kimura Y, Matsumoto K (2001) Effects of erbium,chromium:YSGG laser irradiation on root canal walls: a scanning electron microscopic and thermographic study. J Endod 27(1):9–12. https://doi.org/10.1097/00004770-200101000-00003
81. Schoop U, Goharkhay K, Klimscha J, Zagler M, Wernisch J, Georgopoulos A, Sperr W, Moritz A (2007) The use of the erbium, chromium:yttrium-scandium-gallium-garnet laser in endodontic treatment: the results of an in vitro study. J Am Dent Assoc 138(7):949–955. https://doi.org/10.14219/jada.archive.2007.0291
82. Verdaasdonk RM, van Swol CF, Grimbergen MC, Rem AI (2006) Imaging techniques for research and education of thermal and mechanical interactions of lasers with biological and model tissues. J Biomed Opt 11(4):041110. https://doi.org/10.1117/1.2338817
83. Blanken J, De Moor RJ, Meire M, Verdaasdonk R (2009) Laser induced explosive vapor and cavitation resulting in effective irrigation of the root canal. Part 1: a visualization study. Lasers Surg Med 41(7):514–519. https://doi.org/10.1002/lsm.20798
84. George R, Meyers IA, Walsh LJ (2008) Laser activation of endodontic irrigants with improved conical laser fiber tips for removing smear layer in the apical third of the root canal. J Endod 34(12):1524–1527. https://doi.org/10.1016/j.joen.2008.08.029
85. George R, Walsh LJ (2010) Thermal effects from modified endodontic laser tips used in the apical third of root canals with erbium-doped yttrium aluminium garnet and erbium, chromium-doped yttrium scandium gallium garnet lasers. Photomed Laser Surg 28(2):161–165. https://doi.org/10.1089/pho.2008.2423
86. De Moor RJ, Meire M, Goharkhay K, Moritz A, Vanobbergen J (2010) Efficacy of ultrasonic versus laser-activated irrigation to remove artificially placed dentin debris plugs. J Endod 36(9):1580–1583
87. Varella CH, Pileggi R (2007) Obturation of root canal system treated by Cr, Er: YSGG laser irradiation. J Endod 33(9):1091–1093. https://doi.org/10.1016/j.joen.2007.05.012
88. Ozer SY, Basaran E (2013) Evaluation of microleakage of root canal fillings irradiated with different output powers of erbium, chromium:yttrium-scandium-gallium-garnet laser. Aust Endod J 39(1):8–14. https://doi.org/10.1111/j.1747-4477.2009.00218.x
89. Nagas E, Kucukkaya S, Eymirli A, Uyanik MO, Cehreli ZC (2017) Effect of laser-activated irrigation on the push-out bond strength of ProRoot mineral trioxide aggregate and biodentine in furcal perforations. Photomed Laser Surg 35(4):231–235. https://doi.org/10.1089/pho.2016.4171
90. Mehl A, Folwaczny M, Haffner C, Hickel R (1999) Bactericidal effects of 2.94 microns Er:YAG-laser radiation in dental root

canals. J Endod 25(7):490–493. https://doi.org/10.1016/S0099-2399(99)80288-X
91. Eldeniz AU, Ozer F, Hadimli HH, Erganis O (2007) Bactericidal efficacy of Er,Cr:YSGG laser irradiation against Enterococcus faecalis compared with NaOCl irrigation: an ex vivo pilot study. Int Endod J 40(2):112–119. https://doi.org/10.1111/j.1365-2591.2006.01190.x
92. Peeters HH, De Moor RJ, Suharto D (2014) Visualization of removal of trapped air from the apical region in simulated root canals by laser-activated irrigation using an Er,Cr:YSGG laser. Lasers Med Sci 30(6):1683–1688. https://doi.org/10.1007/s10103-014-1643-z
93. Arnabat J, Escribano C, Fenosa A, Vinuesa T, Gay-Escoda C, Berini L, Vinas M (2010) Bactericidal activity of erbium, chromium:yttrium-scandium-gallium-garnet laser in root canals. Lasers Med Sci 25(6):805–810. https://doi.org/10.1007/s10103-009-0693-0
94. Gordon W, Atabakhsh VA, Meza F, Doms A, Nissan R, Rizoiu I, Stevens RH (2007) The antimicrobial efficacy of the erbium, chromium:yttrium-scandium-gallium-garnet laser with radial emitting tips on root canal dentin walls infected with Enterococcus faecalis. J Am Dent Assoc 138(7):992–1002. https://doi.org/10.14219/jada.archive.2007.0297
95. Zhu L, Tolba M, Arola D, Salloum M, Meza F (2009) Evaluation of effectiveness of Er,Cr:YSGG laser for root canal disinfection: theoretical simulation of temperature elevations in root dentin. J Biomech Eng 131(7):071004. https://doi.org/10.1115/1.3147801
96. Schoop U, Kluger W, Moritz A, Nedjelik N, Georgopoulos A, Sperr W (2004) Bactericidal effect of different laser systems in the deep layers of dentin. Lasers Surg Med 35(2):111–116. https://doi.org/10.1002/lsm.20026
97. Abad-Gallegos M, Arnabat-Dominguez J, Espana-Tost A, Berini-Aytes L, Gay-Escoda C (2009) In vitro evaluation of the temperature increment at the external root surface after Er,Cr:YSGG laser irradiation of the root canal. Med Oral Patol Oral Cir Bucal 14(12):e658–e662
98. Altundasar E, Ozcelik B, Cehreli ZC, Matsumoto K (2006) Ultramorphological and histochemical changes after ER,CR:YSGG laser irradiation and two different irrigation regimes. J Endod 32(5):465–468. https://doi.org/10.1016/j.joen.2005.08.005
99. Lopes FC, Roperto R, Akkus A, Akkus O, Souza-Gabriel AE, Sousa-Neto MD (2016) Effects of different lasers on organic/inorganic ratio of radicular dentin. Lasers Med Sci 31(3):415–420. https://doi.org/10.1007/s10103-015-1862-y
100. Strakas D, Franzen R, Kallis A, Vanweersch L, Gutknecht N (2013) A comparative study of temperature elevation on human teeth root surfaces during Nd:YAG laser irradiation in root canals. Lasers Med Sci 28(6):1441–1444. https://doi.org/10.1007/s10103-012-1203-3
101. Helvacioglu Kivanc B, Deniz Arisu H, Yanar NO, Silah HM, Inam R, Gorgul G (2015) Apical extrusion of sodium hypochlorite activated with two laser systems and ultrasonics: a spectrophotometric analysis. BMC Oral Health 15(1):71. https://doi.org/10.1186/s12903-015-0056-0
102. Schoop U, Barylyak A, Goharkhay K, Beer F, Wernisch J, Georgopoulos A, Sperr W, Moritz A (2009) The impact of an erbium, chromium:yttrium-scandium-gallium-garnet laser with radial-firing tips on endodontic treatment. Lasers Med Sci 24(1):59–65. https://doi.org/10.1007/s10103-007-0520-4
103. Ozkan L, Cetiner S, Sanlidag T (2014) Effect of Er,Cr:YSGG laser irradiation with radial firing tips on *Candida albicans* in experimentally infected root canals. Biomed Res Int 2014:938245
104. Martins MR, Carvalho MF, Vaz IP, Capelas JA, Martins MA, Gutknecht N (2013) Efficacy of Er,Cr:YSGG laser with endodontical radial firing tips on the outcome of endodontic treatment: blind randomized controlled clinical trial with six-month evaluation. Lasers Med Sci 28(4):1049–1055. https://doi.org/10.1007/s10103-012-1172-6
105. Martins MR, Lima RC, Pina-Vaz I, Carvalho MF, Gutknecht N (2016) Endodontic treatment of an autogenous transplanted tooth using an Er,Cr:YSGG laser and radial firing tips: case report. Photomed Laser Surg 34(10):487–493. https://doi.org/10.1089/pho.2015.4061
106. Peeters HH, Mooduto L (2013) Radiographic examination of apical extrusion of root canal irrigants during cavitation induced by Er,Cr:YSGG laser irradiation: an in vivo study. Clin Oral Investig 17(9):2105–2112. https://doi.org/10.1007/s00784-012-0910-2
107. Bago Juric I, Plecko V, Anic I (2014) Antimicrobial efficacy of Er,Cr:YSGG laser-activated irrigation compared with passive ultrasonic irrigation and RinsEndo((R)) against intracanal Enterococcus faecalis. Photomed Laser Surg 32(11):600–605. https://doi.org/10.1089/pho.2014.3767
108. Licata ME, Albanese A, Campisi G, Geraci DM, Russo R, Gallina G (2015) Effectiveness of a new method of disinfecting the root canal, using Er, Cr:YSGG laser to kill Enterococcus faecalis in an infected tooth model. Lasers Med Sci 30(2):707–712. https://doi.org/10.1007/s10103-013-1410-6
109. Peeters HH, De Moor RJ, Suharto D (2015) Visualization of removal of trapped air from the apical region in simulated root canals by laser-activated irrigation using an Er,Cr:YSGG laser. Lasers Med Sci 30(6):1683–1688. https://doi.org/10.1007/s10103-014-1643-z
110. Martins MR, Carvalho MF, Pina-Vaz I, Capelas JA, Martins MA, Gutknecht N (2014) Outcome of Er,Cr:YSGG laser-assisted treatment of teeth with apical periodontitis: a blind randomized clinical trial. Photomed Laser Surg 32(1):3–9. https://doi.org/10.1089/pho.2013.3573
111. Haidary D, Franzen R, Gutknecht N (2016) Root surface temperature changes during root canal laser irradiation with dual wavelength laser (940 and 2780 nm): a preliminary study. Photomed Laser Surg 34(8):336–344. https://doi.org/10.1089/pho.2015.4007
112. Al-Karadaghi TS, Gutknecht N, Jawad HA, Vanweersch L, Franzen R (2015) Evaluation of temperature elevation during root canal treatment with dual wavelength laser: 2780 nm Er,Cr:YSGG and 940 nm diode. Photomed Laser Surg 33(9):460–466. https://doi.org/10.1089/pho.2015.3907
113. Moher D, Hopewell S, Schulz KF, Montori V, Gotzsche PC, Devereaux PJ, Elbourne D, Egger M, Altman DG, Consort (2012) CONSORT 2010 explanation and elaboration: updated guidelines for reporting parallel group randomised trials. Int J Surg 10(1):28–55. https://doi.org/10.1016/j.ijsu.2011.10.001
114. Iglecias EF, Freire LG, de Miranda Candeiro GT, Dos Santos M, Antoniazzi JH, Gavini G (2017) Presence of voids after continuous wave of condensation and single-cone obturation in mandibular molars: a micro-computed tomography analysis. J Endod 43(4):638–642. https://doi.org/10.1016/j.joen.2016.11.027
115. Friedman S, Abitbol S, Lawrence HP (2003) Treatment outcome in endodontics: the Toronto Study. Phase 1: initial treatment. J Endod 29(12):787–793. https://doi.org/10.1097/00004770-200312000-00001
116. Farzaneh M, Abitbol S, Lawrence HP, Friedman S, Toronto S (2004) Treatment outcome in endodontics-the Toronto Study. Phase II: initial treatment. J Endod 30(5):302–309. https://doi.org/10.1097/00004770-200405000-00002
117. Kakehashi S, Stanley HR, Fitzgerald RJ (1965) The effects of surgical exposures of dental pulps in germ-free and conventional laboratory rats. Oral Surg Oral Med Oral Pathol 20(3):340–349. https://doi.org/10.1016/0030-4220(65)90166-0
118. Sabeti MA, Nekofar M, Motahhary P, Ghandi M, Simon JH (2006) Healing of apical periodontitis after endodontic treatment

with and without obturation in dogs. J Endod 32(7):628–633. https://doi.org/10.1016/j.joen.2005.12.014

119. Tsesis I, Faivishevsky V, Kfir A, Rosen E (2009) Outcome of surgical endodontic treatment performed by a modern technique: a meta-analysis of literature. J Endod 35(11):1505–1511. https://doi.org/10.1016/j.joen.2009.07.025
120. Orstavik D (1996) Time-course and risk analyses of the development and healing of chronic apical periodontitis in man. Int Endod J 29(3):150–155. https://doi.org/10.1111/j.1365-2591.1996.tb01361.x
121. Segura-Egea JJ, Gould K, Sen BH, Jonasson P, Cotti E, Mazzoni A, Sunay H, Tjaderhane L, Dummer PM (2016) Antibiotics in endodontics: a review. Int Endod J 50(12):1169–1184. https://doi.org/10.1111/iej.12741
122. Segura-Egea JJ, Gould K, Sen BH, Jonasson P, Cotti E, Mazzoni A, Sunay H, Tjaderhane L, Dummer PMH (2017) European Society of Endodontology position statement: the use of antibiotics in endodontics. Int Endod J 51(1):20–25. https://doi.org/10.1111/iej.12781
123. Stabholz A, Zeltser R, Sela M, Peretz B, Moshonov J, Ziskind D (2003) The use of lasers in dentistry: principles of operation and clinical applications. Compend Contin Educ Dent 24(12):935–948 quiz 949
124. Vier FV, Figueiredo JA (2004) Internal apical resorption and its correlation with the type of apical lesion. Int Endod J 37(11):730–737. https://doi.org/10.1111/j.1365-2591.2004.00830.x
125. Odor TMWT, Pitt Ford TR, McDonald F (1996) Pattern of transmission of laser light in teeth. Int Aust Endod J 29(4):228–234. https://doi.org/10.1111/j.1365-2591.1996.tb01374.x
126. Onay EO, Orucoglu H, Kiremitci A, Korkmaz Y, Berk G (2010) Effect of Er,Cr:YSGG laser irradiation on the apical sealing ability of AH Plus/gutta-percha and Hybrid Root Seal/Resilon Combinations. Oral Surgery Oral Med Oral Pathol Oral Radiol Endod 110(5):657–664. https://doi.org/10.1016/j.tripleo.2010.05.062
127. Schunemann HJ, Oxman AD, Brozek J, Glasziou P, Jaeschke R, Vist GE, Williams JW Jr, Kunz R, Craig J, Montori VM, Bossuyt P, Guyatt GH, Group GW (2008) Grading quality of evidence and strength of recommendations for diagnostic tests and strategies. BMJ 336(7653):1106–1110. https://doi.org/10.1136/bmj.39500.677199.AE
128. Gutmann JL, Solomon E (2009) Journal of endodontics. Guest editorial. J Endod 35(8):1093. https://doi.org/10.1016/j.joen.2009.06.001
129. Mileman PA, van den Hout WB (2009) Evidence-based diagnosis and clinical decision making. Dentomaxillofac Radiol 38(1):1–10. https://doi.org/10.1259/dmfr/18200441
130. Suebnukarn S, Ngamboonsirisingh S, Rattanabanlang A (2010) A systematic evaluation of the quality of meta-analyses in endodontics. J Endod 36(4):602–608. https://doi.org/10.1016/j.joen.2009.12.019
131. Ferreira PH, Ferreira ML, Maher CG, Refshauge K, Herbert RD, Latimer J (2002) Effect of applying different "levels of evidence" criteria on conclusions of Cochrane reviews of interventions for low back pain. J Clin Epidemiol 55(11):1126–1129. https://doi.org/10.1016/S0895-4356(02)00498-5
132. Richards D (2009) GRADING—evels of evidence. Evid Based Dent 10(1):24–25. https://doi.org/10.1038/sj.ebd.6400636
133. Kazdin AE (1999) The meanings and measurement of clinical significance. J Consult Clin Psychol 67(3):332–339. https://doi.org/10.1037/0022-006X.67.3.332
134. Elwyn G, Frosch DL, Kobrin S (2016) Implementing shared decision-making: consider all the consequences. Implement Sci 11:114