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ORIGINAL ARTICLE

The impact of an erbium, chromium: yttrium-scandium-gallium-garnet laser with radial-firing tips on endodontic treatment

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Abstract Radial-firing tips should allow a more homogeneous laser irradiation of root canal walls. The aim of the study was to assess the effects of erbium, chromium: yttrium-scandium-gallium-garnet (Er,Cr:YSGG) laser irradiation in conjunction with those newly designed tips. The investigation comprised bacteriology, morphological evaluations and temperature measurements. Root canals were inoculated with two test strains and laser irradiated with power settings of 0.6 W and 0.9 W and a repetition rate of 20 Hz. Subsequently, the samples were subjected to microbiological evaluation. The morphological changes of the canal walls were assessed by scanning electron microscopy. To reveal possible thermal side effects, we carried out temperature measurements. The bacteriological evaluation revealed a decisive disinfectant effect. Scanning electron microscopy showed the homogeneous removal of smear layer from the root canal walls. The temperature rise at the root surface during the irradiation was moderate, yielding 1.3°C for the 0.6 W setting and 1.6°C for the 0.9 W setting. The investigations indicated that the Er,Cr: YSGG laser, in conjunction with radial-firing tips, is a suitable tool for the elimination of bacteria in root canals and for the removal of smear layer.

Keywords Endodontics · Root canal · Laser · Radial-firing tips · Bacteriology · Scanning electron microscopy

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Introduction

Since bacteria are the most important elicitors of periapical infections, the decisive objective in endodontic therapy is the disinfection of the root canal and the three-dimensional network of dentinal tubules. From the infected pulp tissue bacteria penetrate into the deeper layers of root dentine and propagate a periapical inflammation with subsequent destruction of the adjacent connective tissues [1–3].

The local microenvironment favours the selection of relatively few bacterial species, which can survive and proliferate, being out of reach of the host's immune response [4–8]. Even rinsing solutions applied during conventional root canal treatment only partly affect those bacteria. The pathogenic microorganisms are able to penetrate the root dentine up to a depth of more than 1 mm, whereas disinfecting solutions reach a depth of only approximately 100 μm [9, 10]. In addition, bacteria such as *Enterococcus faecalis* have the capability to form intra- and extra-radicular biofilms, which makes them even harder to control [11–13]. These facts are often responsible for those cases that are therapy resistant from the beginning or that

end up as long-term failures after endodontic treatment has been accomplished.

Considering this, the disinfection of the root canal, including the most distant areas of the tubular system, can be regarded as a major challenge in today's endodontic treatment and is of fundamental importance for the prolonged preservation of endodontically treated teeth. The use of lasers in the field of endodontology represents an innovative approach to match these requirements. In general, dental lasers provide greater accessibility of formerly unreachable parts of the tubular network, due to their better penetration into dentinal tissues [14–16]. Although a wide spectrum of wavelengths has been investigated since the early 1980s, the neodymium: yttrium-aluminium-garnet (Nd:YAG) laser can be regarded as the best-established system in endodontic treatment. Owing to the laser's wavelength of 1,064 nm, flexible conductors can be used for application in narrow and bent root canals. This laser yields a bactericidal effect not only on root canal surfaces but also in the deeper layers of dentine. Several studies by White et al. [17], Rooney et al. [18], Gutknecht et al. [19], Moritz et al. [20] and Schoop et al. [21] have proved the high bactericidal effect of the Nd:YAG laser.

Diode lasers are comparable to the Nd:YAG laser in terms of effectiveness. They emit at a wavelength of 810 nm or 980 nm and possess satisfying bactericidal capabilities, as shown by Moritz et al. [22] and Schoop et al. [21, 23].

For the removal of dental hard tissue the erbium:yttrium-aluminium-garnet (Er:YAG) and the erbium, chromium: yttrium-scandium-gallium-garnet (Er,Cr:YSGG) lasers provide suitable wavelengths. Emitting at 2,940 nm and 2,780 nm, respectively, these lasers act through photoablation, since their wavelengths correlate closely with the absorption maximum of the water contained by the hydroxyapatite. When irradiated, water contained in the dental hard tissue evaporates instantaneously and thereby ablates the surrounding tissue with only minimal thermal side effects. This has been demonstrated in a study by Hibst and Keller [24].

Although primarily used for the preparation of dental hard substances, the erbium wavelengths can also be applied in the field of endodontic treatment. The development of flexible fibre tips allows the irradiation of even narrow or bent root canals. Hibst et al. [25] proposed the use of the Er:YAG laser in endodontics, and later studies by Schoop et al. [21, 26, 27] confirmed the laser's qualification.

Several papers have focused on caries removal and cavity preparation using the Er,Cr:YSGG laser [28–30], whereas authors such as Yamazaki et al. [31] and Kimura et al. [32] described the morphological changes encountered in irradiated root canal walls. A study by Schoop et al. [21] illustrated the bactericidal potential of the Er,Cr:YSGG laser applied to root dentine samples.

Although favourable results have been achieved with all those wavelengths, the delivering fibre tips still show some room for improvement. Owing to total reflectance at the fibre walls, the laser beam is expanded to a certain degree when leaving the end of the fibre tip. However, the biggest part of the laser light will still be propagated straight towards the apex of the root. By conducting the irradiation of the root canal in spiral movements and through a certain tilting of the fibres, one can minimize this effect, to a certain extent, and a sufficient energy density at the root canal walls can be achieved. Striving for the improvement of the established delivery systems, a new generation of fibre tips has been developed that allow a more homogeneous irradiation of the root canal walls. The ends of these radial-emitting fibre tips show a conical outline with a cone angle of 60°. The laser light, therefore, is expanded to a broad cone, facilitating an even coverage of the whole root canal wall.

This study examined the bactericidal, morphological and thermal effects of the Er,Cr:YSGG laser, utilizing these radial-firing tips in root canals. To evaluate the antimicrobial effect of the laser, we performed bacteriological in vitro experiments with two different species. Morphological alterations on dentinal surfaces were recorded by use of an environmental scanning electron microscope (ESEM), and the thermal effects caused by laser irradiation were measured with a thermocouple.

Materials and methods

Sample preparation

Sixty extracted human teeth with one root were endodontically prepared. The teeth were stored in physiological saline solution after the extraction. Subsequently, trepanation and orthograde enlargement of the root canal to ISO 70 were performed. During the preparation process, the root canals were rinsed with physiological saline solution only; no EDTA was applied. The prepared teeth were assigned to six different experimental groups and treated accordingly.

Bacterial inoculation

The samples were steam sterilized (Melatronic 23, Melag, Berlin, Germany) at 134°C for 10 min for the removal of all pre-existing germs. Following this step, the root canals were inoculated with 10 μl of either of the two test strains, *Escherichia coli* (ATCC 10536) or *Enterococcus faecalis* (ATCC 29212) with a micropipette. The initial bacterial count was 10^8 colony forming units per millilitre (CFU/ml).

The inoculated teeth were sealed with wax and then placed into sterile microcentrifuge tubes containing 100 μl of a physiological saline solution. After an incubation period of 4 h at 35°C, the teeth were taken out of the Eppendorf tubes, and the wax seal was removed.

Laser irradiation

Laser irradiation was performed in the root canal. An Er,Cr:YSGG laser (Waterlase MD, Biolase, San Clemente, USA), emitting at a wavelength of 2,780 nm, was used. In this device, pulse energy can be varied between 25 mJ and 300 mJ, and the repetition rate can be adjusted between 10 Hz and 50 Hz. This results in an output power of 0.5–8 W. For our investigation, the device was equipped with exchangeable 200 μm fibre tips with a conical outline, allowing radial emission of the laser beam.

The actual laser power emitted at the fibre tip was measured by a wattmeter (FieldMaster, Coherent Inc., Auburn, CA, USA) before each irradiation to ensure stable and standardized power outputs. Laser irradiation was performed in the root canal. For each strain, 20 samples were treated. Two groups of ten samples each underwent laser treatment at a setting of 2 W (100 mJ) and 3 W (150 mJ) as indicated on the display of the laser unit, corresponding to an actual power output of 0.6 W (30 mJ) and 0.9 W (45 mJ), measured directly at the end of the fibre tip. The pulse rate was the same for all groups (20 Hz). The rather big difference between the laser setting and the actual power output can be explained by the calibration factor of the fibre, which ranges around 70%. That means that roughly two-thirds of the laser energy are absorbed within the fibre tip.

Each sample was treated with one lasing cycle, which comprised five irradiations of 5 s duration with a 20 s break in between. For irradiation the optical tip was inserted as far as the apex. Then, the laser was activated, and the root canal was continuously radiated from apical to coronal, in slow, circling movements. By means of this procedure the irradiation of the entire root canal could be ensured. For each test microorgansim, ten samples served as a control group. Those samples were treated the same way as the actual laser samples, except for the very irradiation itself. That is to say, the laser fibre was introduced into the canal without activating the laser device.

The irradiation was done by hand and always by the same investigator to ensure comparability between the sample groups within the actual study and preceding investigations.

Bacteriological evaluation

Immediately after the laser treatment the root canal was rinsed with 1 ml of a physiological saline solution, and the eluate was collected in a microcentrifuge tube. Finally, the bacterial count was determined. The extracted fluid was diluted in log 10 steps. From each dilution, 20 μl was applied to culture plates (sheep agar plates, bioMérieux, Marcy l'Etoile, France) and incubated for 24 h at 37°C. The colonies were then counted, and the total number of bacteria (colony forming units per millilitre of the extraction fluid) was assessed. The lowest detection level of bacteria was 5×10^2 CFU/ml.

Temperature measurements

To assess the thermal impact of the Er,Cr:YSGG laser irradiation, we measured the temperatures. For this purpose, five samples were used for each power setting. The teeth were mounted on an even thermocouple (manufactured by the Technical University of Vienna and provided with a digital thermometer) measuring 10 mm by 10 mm using a silicon-based heat-conductive compound (Dow Corning 340 Heat Sink Compound, Dow Corning, Midland, Michigan, USA). During the irradiation procedure, which was carried out in the same way as the irradiation of the inoculated samples, the maximum temperature increase (starting from a room temperature of 21°C) was recorded by a digital thermometer (TMG-1 device, manufactured by the Technical University of Vienna) with a sampling rate of 20 Hz and a sensitivity of 0.1°C. The average value and the standard deviation of the five measurements per laser setting were calculated subsequently.

Environmental scanning electron microscopy

An additional 20 samples were subdivided into two groups (0.6 W and 0.9 W each) and prepared as described above (except for the bacteriological procedure). The samples were cut longitudinally with a diamond-coated band saw ("Trennschleif System", Exakt, Norderstedt, Germany) then submitted to scanning electron microscopy so that we could evaluate the morphological changes induced by the laser irradiation. The specimens were assessed with an environmental scanning electron microscope (ESEM XL30, Philips, Eindhoven, The Netherlands) working with mild negative pressure and without sputtering of the samples, thus facilitating the assessment of native samples and the minimization of artefacts. Pictures were taken at different magnifications.

Results

Bacteriology

Table 1 shows the results of the bacteriologic tests on *Escherichia coli* and *Enterococcus faecalis*.

Table 1 Bacterial counts of *Escherichia coli* and *Enterococcus faecalis*. For each irradiation power applied, the number of specimens and the range of CFUs/ml is indicated

Parameter	*Escherichia coli* (CFU/ml)						*Enterococcus faecalis* (CFU/m)l					
	Below detection level	10^3	10^4	10^5	10^6	10^7	Below detection level	10^3	10^4	10^5	10^6	10^7
Control				6	4					3	6	1
Er,Cr:YSGG; 0.6 W	5	5					5	2	1	2		
Er,Cr:YSGG; 0.9 W	10						4	4	2			

Samples are rated in log-steps of the colony counts (CFU/ml), and the specific radiation power applied.

The results of the control group of both test strains showed colony counts ranging between 10^5 CFU/ml and 10^6 CFU/ml, demonstrating a decrease of 2 to 3 log-steps through the inoculation and incubation process and the further processing of the samples.

As far as *Escherichia coli* was concerned, the Er,Cr:YSGG laser succeeded in a major reduction of the test bacterium, even at the lower output power of 0.6 W. At the higher power value (0.9 W), the impact was even more considerable, yielding a complete reduction to below the detection level.

The laser device tested was also effective in reducing the gram positive *Enterococcus faecalis*. At 0.6 W the Er,Cr:YSGG laser was capable of removing the germ to an extent of 3 to 4 log-steps (compared with the control group) in a major part of the samples. The higher output power (0.9 W) conferred only a slight improvement in terms of disinfectant effectiveness compared with the sample group irradiated with a power of 0.6 W. For *Enterococcus faecalis*, complete reduction to below the detection level was, however, achieved in none of the groups.

Temperature measurements

When an output power of 0.6 W was chosen, the irradiation of the samples resulted in an average temperature rise of 1.3°C at the root surface. The higher output of 0.9 W yielded an average temperature rise of 1.6°C at the root surface.

Table 2 Temperature rise at the root surface. The averages and standard deviations have been calculated from five individual measurements per power setting

Device	0.6 Watt	0.9 Watt
Er,Cr:YSGG	1.3°C±0.4°C	1.6°C±0.5°C

Table 2 presents the temperature measurements. All the measurements were carried out at a room temperature of 21°C; thus, they refer to an initial sample temperature of 21°C. For instance, the value 1.3°C stands for a temperature rise to 22.3°C. Although a higher irradiation power results in a stronger temperature increase at the sample surface, the temperature stays within safe boarders.

Environmental scanning electron microscopy

Figure 1 shows a length cut through a root that has been irradiated with the Er,Cr:YSGG laser at 0.6 W using a radial-firing tip (magnification ×100). At the left and right margins of the picture, the cut surface of the root dentine can be seen. The root canal surface exhibits the typical rough structure after the removal of the adhering smear layer.

Figure 2 gives a detailed view of the root canal wall at 2,000-fold magnification after irradiation with 0.6 W. The dentinal tubules have been partly exposed; other portions of the root canal wall are still covered with a thin smear layer.

When the output power was increased to 0.9 W, the low magnification reveals the same basic surface structure as depicted in Fig. 1. The cut surfaces of the root dentine are discernible alongside a comparably clean and even surface (Figure 3).

Figure 4 shows a detail of a root canal irradiated with 0.9 W. Most of the dentinal tubules have been exposed, and no cracks or signs of melting can be discerned.

Discussion

Successful endodontology relies, to a great extent, on complete cleaning of the root canal. Infected dentine and pulpal tissue can endanger therapy outcome. Conventional root canal treatment aims at the removal of the infected pulp and dentine layers by using mechanical techniques and bactericidal irrigants. In this context, the method of

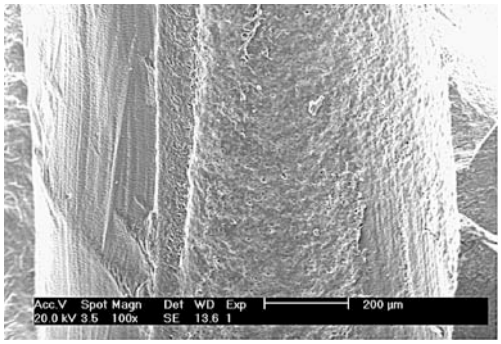

Fig. 1 SEM picture of a root canal irradiated with an output power of 0.6 W. Magnification ×100

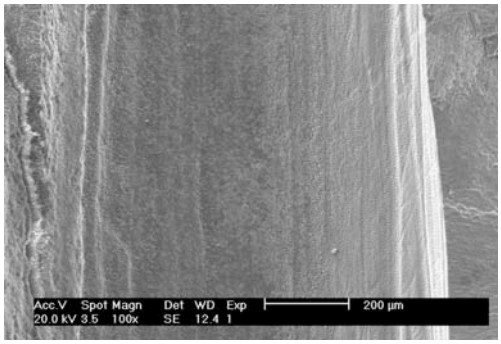

Fig. 3 SEM picture of a root canal irradiated with an output power of 0.9 W. Magnification ×100

bactericidal rinsing encounters a major problem: studies by Kouchi et al. [9] have shown that bacteria colonize the periluminal dentine up to a depth of 1,100 µm. Chemical disinfectants penetrate only 100 µm into the dentine, as indicated by Berutti et al. [10]. In addition, bent root canals or side branches can be obstacles in the conventional root canal treatment. The utilization of lasers helps to overcome this issue, as already pointed out in the Introduction section. The high penetration depth of the laser light in the dentinal tissue seems to be the most appropriate explanation for the satisfying bactericidal effect of different laser wavelengths. One possible explanation for this kind of light propagation is given by Vaarkamp et al. [15], Odor et al. [16] and Kienle et al. [33]. These authors have described the ability of enamel prisms and dentine tubules to scatter light within dental hard tissues. In fact, it was possible to demonstrate the effect of Nd:YAG laser irradiation on bacteria through indirect irradiation [34].

The use of laser wavelengths suitable for the preparation of dental hard substances could add another interesting aspect to the field of root canal cleaning. In an in vitro study [27], Schoop et al. described the impacts of Er:YAG laser irradiation on root canal walls and the bactericidal effect of the wavelength. A comparative study confirmed the high bactericidal potential of both the Er:YAG- and the Er,Cr:YSGG lasers [21].

Irrespective of the wavelength utilized, the beam geometry at the fibre output corresponds to a narrow cone, delivering the highest radiation density straight towards the apex. Considering the fact that the diameter of the instrumented root canal is rather larger than the fibre diameter, a larger portion of the laser beam can be directed at the root canal walls just by tilting the fibre tip during the irradiation procedure. Although a satisfying bactericidal effect can thus be achieved, the light distribution on the canal surface still seems to be rather irregular. In fact, SEM investigations of root canal surfaces that have been irradiated with Er:YAG- or Er,Cr:YSGG lasers show isolated irregularities like molten and recrystallized portions of dentine or a distinct crack formation [21, 26, 27].

Through the introduction of a new radial-firing fibre tip, the mode of light emission in the root canal has been improved. Owing to the conical shape of the fibre tip, the laser light is emitted in the form of a broad cone with an angle of about 60°, according to the manufacturer's information, allowing a more uniform coverage of the whole dentinal surface.

The aim of our study was to evaluate the effectiveness of Er,Cr:YSGG laser irradiation applied through a radial-firing fibre tip with a diameter of 200 µm. Owing to the comparably high attenuation of the laser beam by the fibre tips, the effective output evaluated was 0.6 W and 0.9 W,

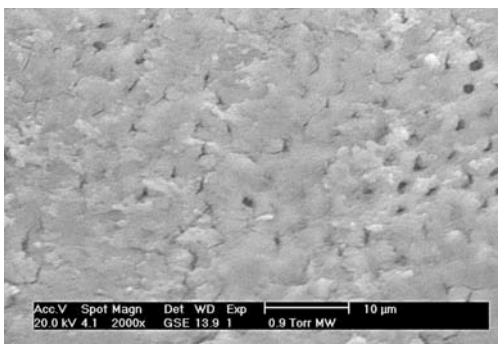

Fig. 2 SEM picture of a root canal irradiated with an output power of 0.6 W. Magnification ×2,000

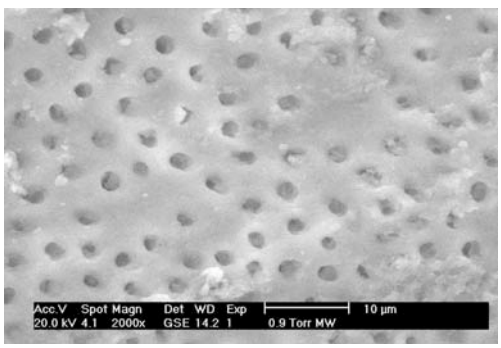

Fig. 4 SEM picture of a root canal irradiated with an output power of 0.9 W. Magnification ×2,000

as explained above in Materials and methods, Laser irradiation.

In fact, the higher setting had to be applied in order to achieve a reduction of *Escherichia. coli* to below the detection level in all samples. When the samples with *Enterococcus faecalis* were irradiated, again a remarkable antibacterial effect was observed; complete reduction to below the detection level was, however, not accomplished in all samples. The results achieved are comparable to those described in an earlier study [35], where conventional 300 μm fibre tips were applied in conjunction with a remarkably higher power output (1 W and 1.5 W, respectively).

On the other hand, the negligible temperature rise at the root surface illustrates the low energy dosage delivered to the samples. The temperature rise at the root surface did not exceed 1.6°C; therefore, possible damage to the surrounding periodontal tissues could be excluded. In addition, excessive heating of the entire sample obviously could not be regarded as the decisive reason for the bactericidal effect.

Owing to the high absorption of the Er,Cr:YSGG laser's radiation in water, the penetration depth in dentine should be rather restricted, in contrast to other lasers such as the Nd:YAG or the diode. One possible explanation for the good bactericidal effect in this study could, therefore, be a lack of penetration of the test bacteria into the dentinal tubules, because the samples were incubated only for 4 h prior to laser irradiation. However, the Er:YAG- and the Er,Cr:YSGG lasers have also shown good bactericidal potential when the irradiation has been carried out indirectly through a dentine layer of 1 mm [21]. Another explanation for the effect, particularly on *Enterococcus faecalis*, could be a certain degree of conduction of the laser light within the dentinal tubules, resulting in a higher penetration depth. Other factors, such as shock waves or cavitation effects, have at least been reported for other laser devices [36, 37] and could represent a further explanation for the actual impacts of Er,Cr:YSGG laser irradiation. In any case, further investigations are necessary to clarify the exact interactions of laser light and bacteria.

Scanning electron microscopy revealed the ability of the Er,Cr:YSGG laser applied with a radial-firing tip to remove smear layer and debris from the root canal wall and to open up the orifices of dentinal tubules. This effect should facilitate tight root canal sealing. We used the laser as an adjunct to conventional root canal preparation. Although the laser was applied without water spray, a very homogeneous impact on the root canal walls, with no signs of melting or cracking, was observed. This leads us to the conclusion that the expansion of the beam by the tip geometry favours a higher energy distribution at the root canal walls.

Although the laser was able to reduce strongly the number of viable bacteria in the root canal, the bactericidal potential was slightly inferior compared to the same device applied through a conventional 300 μm fibre tip. Since the total temperature rise was negligible, there seems to be room for a laser application through radial-firing tips with a higher diameter of 300 μm or 400 μm, allowing a higher energy output ranging around 1.5 W. When those fibre tips become available, additional investigations will be necessary.

Conclusion and clinical relevance

Considering all the facts described, one can conclude that the wavelength and delivery system tested in our study may be suitable for the cleaning and disinfection of root canals and can be safely applied, if the common precautions for laser application are observed and the applied energy and irradiation time stay within the proposed range. For the results to be confirmed further, and for the wavelengths to be investigated under in vivo conditions, clinical studies are necessary.

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