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Effective application of suitable single pulse of Nd:doped lasers for cleaning of initial carious lesions of human teeth. Experimental study

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Effective application of suitable single pulse of Nd:doped lasers for cleaning of initial carious lesions of human teeth. Experimental study

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Abstract. We show via detailed experimental investigations that the single pulse from Nd:YAG and Nd:Glass lasers (wavelength 1.06 μm, free lasing operation) are suitable for efficient cleaning initial carious lesions (1 - 3 mm in diameter) on tooth enamel. The cleaning is in combination with tooth preparation for final healing procedures – formation of desired hole and antibacterial cleaning. The measured heating of the tooth chamber is in acceptable limits and crack formation is avoided. The investigation includes laser irradiation with single pulses of energy of ~2 to 5 J, energy density of ~50 to 130 J/cm^2 and pulse duration of ~500 ns – 2 ms. In further development of the topic, as a second part of this article, we propose algorithm for application of the discussed cleaning.

1. Introduction

Lasers have traditionally been of interest for use in dental tissue healing procedures. Their potential for such treatment is the subject of continuous research and development [1,2]. However, detailed articles note the need to accumulate experimental and theoretical data and to accurately compare them with traditional dental caries removal. The wavelengths of CO_2 gas lasers at 10.6 μm and Er^{3+}-doped solid-state lasers at 2.9 μm, extensively studied in the literature [1-3], are more advantageous in terms of the appropriate wavelength for lesion treatment. Nevertheless, Nd:Crystal (Nd:YAG; Nd:YAP) and Nd:Glass lasers (wavelength ~1.06 μm) are also established as lasers with great potential for dental applications. In addition, their light has also shown excellent applications in bactericidal therapy of teeth [4], as well as increased efficiency of ablation of pigment caries (natural, artificial) [2]. An important advantage of the noted lasers for use in dentistry is that from a technical point of view they are well developed, not expensive, reliable, compact and easy to apply, being very suitable for incorporation into fiber-based medical devices. Furthermore, they are well available as commercial dental devices (e.g., Fotona, Slovenia).

The work shows that the discussed Nd^{3+}-doped lasers are suitable for effective cleaning with a single laser pulse of initial carious lesions (i.e., ~1 to 3 mm in diameter), also in combination with preparation for final treatment procedures. The subject under consideration is divided by us into two parts in two separated articles - the one reported here is the first part and is mainly related to the results of the experimental studies of the noted problems, and the next - the second part [5] deals with the analytical description and analysis. As discussed in the following sections, such treatment with a microsecond light pulse natural to Nd^{3+}-doped lasers and with 1 to 4.5 J (energy density ~60-120 J/cm^2) allows good cleaning also with preparation of the lesions for the final treatment procedure, without problematic heating of the tooth chamber and enamel cracking. Although the treatment of initial lesions of the size noted is not a typical case in dental practice, the results shown in this work indicate that such cleaning can be used effectively in very real cases. Such cases involve continuous monitoring (almost weekly) of the selected patient's teeth, especially those of children.

The general problem associated with cleaning carious lesions with lasers is the heating of the pulp chamber. Therefore, it is important to find the appropriate range, if possible, of laser parameters that will provide cleaning of the lesion with noted tooth preparation without dangerously increasing the temperature of the pulp chamber. As stated in the literature [1,2], increasing the temperature of the chamber by ~8-10^{0}C in 10 s, i.e., increasing it to 42.5^{0}C – 45^{0}C, causes necrosis of the soft tissues inside with all the resulting problems. With light pulses of relatively high energies (~4-5 J), such as the cases described in the paper and the initial lesions, another problem to consider is the formation of a "crack" in the enamel (figure 1 (e)). Such a fracture can, over time, destroy the tooth. In our paper [7], this issue was discussed in detail and a methodology to eliminate the appearance of cracks also at high pulse energy was proposed and demonstrated.

Instead of using a simple single pulse of a given energy, another developed technique applies a series of low-energy sub-pulses of the order of ~0.1 J in a time interval of 0.1-0.3 s [2], with a total irradiation time of a few seconds. The cleaning of this type, point-by-point, is time-varied on the treated part of the lesion [2]. The treatment time is longer, requires consistent monitoring during the illumination, and is also associated with patient discomfort. The use of the techniques noted as examples have their place in practice, each with corresponding advantages and problems.

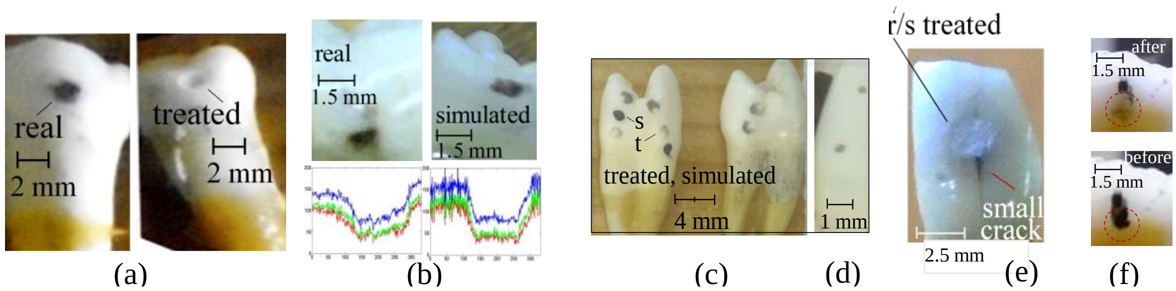

Figure 1. Examples of lesions and treatment with our Nd:doped lasers: (a): left - real small carious lesion, right - good cleaning after treating similar lesion by incident pulse energy 2.6 J; ≈100 J/cm^2 (cleaning by forming conical hole with diameters ≈1.6 mm (outer) and ≈0.7 mm (inner), depth ≈0.5 mm; (Gaussian laser); (b) - left - real carious lesion, right - simulation by appropriate darkening, below - the reflection curves of the real and simulated lesion; 1 (c)-left: ~1.4 mm simulated lesion "s", and after treatment "t" by incident pulse of energy 2 J; ≈120 J/cm^2, formed near cylindrical holes (diameter 1.4 mm, depth ≈0.25 mm, (multimode laser); (d) treatment with energy 0.18 J; 140 J/cm^2, focusing in a spot of 0.4 mm; (e) - 2.1 mm lesion treated by pulse with 4.6 J; ~ 125 J/cm^2 (multi-mode laser); good cleaning, but with crack initiation; almost cylindrical hole (2.1 mm outer and 1.9 mm inner), depth ≈ 0.3 mm; (f) top - treatment by series of 10 pulses /0.4 Hz; total energy ~ 3 J; 13 J/cm^2; bottom - the initial lesion.

Our focus in this work is on single laser pulse processing emitted by Nd:doped lasers. Such pulses are a typical and natural mode of operation - the so-called "free laser mode" (FL mode, student book). The light is emitted in a single pulse of duration ~ 0.3 - 5 ms, composed of a series of very short sub-pulses, each of few μs duration and with μs interval (figure 4 (c)). At such a short time interval, the heat in the tooth matter cannot dissipate and the response of the treated area is equivalent to the action of a single pulse with the summed energy of the subpulses for the entire duration of the illumination. In our work, a Gaussian point mode Nd:YAG laser was used for the low energy emission of 0.5 -1.8 J, and a multi-mode Nd:Glass laser was used for the high energy emission (2- 4.5 J) (see figure 4).

2. Presentation and discussion of our experimental results of single laser pulse treatment

Obtained summarized selected results from the treatment of the starting lesions, with the chosen lasers pulse energetic parameters, are illustrated in figure 1 - in the typical range, for our consideration. The treated lesion in figures 1 (a) and 1 (c) is completely cleaned, in contrast to figure 1 (f), with almost the same lesion and total energy. Especially for the single pulse treatment we varied the incident pulse energy in the range of 1.5 - 5 J, the pulse duration between 0.5 - 2 ms, the energy density between 40 - 120 J/cm^2 for the laser spot and the lesion diameter from 1 to 2.7 mm (when treated with appropriate focusing with a 12 cm focal length lens).

3. Methods and materials of the investigation

Figures 1 (a) and 1 (c) show the feasibility of good lesion cleaning with a single laser pulse of appropriate energy and focusing. The typical depth of the hole formed is ~ 0.3 mm. The hole is heated with the pulse to more than a few hundred degrees, thus also providing bactericidal cleaning [4]. This hole is very suitable for treatment with photo polymerizing dental materials. The one given in figure 1(e) shows a real lesion with d ≈ 2.1 mm and good treatment with a single pulse of 4.6 J. The conical shape is related to the Gaussian shape of the distribution of the acting energy density (figure 4 (a)). In contrast, in the multimode laser beam (the case of figure 1 (c) and figure 1 (e)), the energy density distribution in the beam cross section is practically homogeneous (figure 4 (b)) and the hole formed has a practically cylindrical geometry. For the low light energy cases of 1.5 - 3 J, we used lesion reconstruction for several (2-3) exposures.

The examples shown, part of a series of our experiments, confirm that the energy range of 1.5 - 5 J and density of 40 - 120 J/cm^2 of pulsed Nd:YAG and Nd: Glass are suitable parameters to achieve a good cleaning of initial carious lesions (1-3 mm) with the formation of the necessary hole to complete the treatment (a spatially small cone with a lesion diameter at the top, e.g. 1.5 mm, a bottom diameter of 0.7 mm and a height of 0.3 mm). Higher energy than given leads to crack formation and (figure 5) to unacceptable heating of the pulp chamber (higher than 10^{0}C).

The analysis, which takes into account the evolution of hard dental tissue ablation [1,2,4,6] in the case of treatment with microsecond laser pulses, shows that after a certain irradiation time (~ several hundred μs) a plume of ablation particles is formed. Scattering of light by these particles results in energy loss. In addition, a small part of the scattered light illuminates and heats the bottom of the hole. This portion of the light raises the temperature of the contact dentin and heat is transferred through the dentin to the pulp chamber wall, as considered below.

We will consider a case of extracted teeth with the soft tissues in the inner part of the tooth removed and the tooth cleaned, in order to use a heat meter that is in contact with the inner cleaned part of the pulp chamber wall (figure 3). Three different types of teeth (2-3 samples per type) were investigated: molars, premolars and incisors. Some examples are shown in figure 2.

Figure 2. Typical examples of prepared teeth's samples.

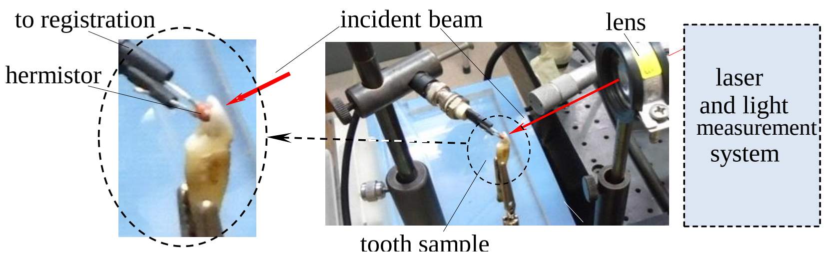

Figure 3. Photographs of the experimental set-up with notations in the text.

The measurements are with Coherent Field Max II - TOP energy meter and Rigol DS1202CA 2-channel 200 MHz Digital Oscilloscope. Two home-made lasers, Nd:YAG and Nd:Glass, operating in FL mode at 1.064 μm were used; the first one with pulse energy from 50 mJ to 2 J and pulse length of ~ 500 μs, repetition rate up to 2 Hz, Gaussian mode spatial distribution (figure 4 (a)). The second - multi-mode Nd:Glass laser (spatial energy distribution in figure 4 (b)), has pulse energy from 3 J to 10 J (used to 5 J) and pulse duration of ~1 – 2 ms. The registration of spatial distribution was done using our spot marking - scanning technique. Typical temporal emission oscillograms of our FL mode Nd:YAG and Nd:Glass lasers are shown in figure 4 (c). The diameter of the laser beam spots on the tooth surface is controlled by appropriately focusing with a 12 cm focal length lens to match the lesion diameter. We use a special homemade electronic device for temperature measurement, which has a very small spherical thermistor with a diameter of about 2 mm as the sensor part (shown in figure 3). This system provides measurements with a sensitivity accuracy of 0.1^0C and a response time on the order of ~1 s. We also assume, as in the literature [2,6], that limiting the pulp soft tissue temperature to 10^0C (for ~10 s) above normal (35-36^0C in the mouth) results in soft tissue necrosis in the pulp chamber. To measure reflection and scattering on the tooth surface for high-energy light (Nd:YAG~0.5 - 5 J, 0.5 ms), we prepared a very thin aluminum foil cover onto the tooth with a small hole entry and at small angle below the lesion. For a lesion size of ~3 mm, the typical losses are ~10% (varying to 20% for some samples).

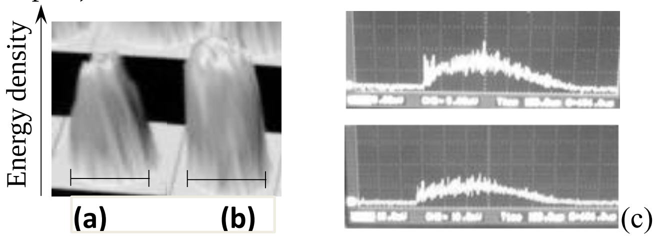

Figure 4. Spatial energy density distribution (3D profile); length of measuring line 1.6 mm: (a) spot of focused Gaussian beam; (b) multimode beam spot; (c) – oscilloscope traces: X-scale time - 100 µs/div, Y-axes - intensity; top–for energy 5 J, bottom – 2.4 J.

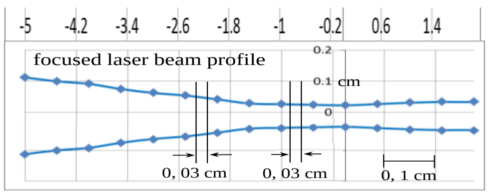

Figure 5. Energy density distribution in the cross section along the Gaussian light beam focused with a 12 cm lens, red laser light (632.8 nm). The focused light at a distance of ~1 mm is a parallel beam.

4. Experimental investigations of lesion cleaning and pulp chamber wall heating

The measurement technique has already been described. In the case of heating of the pulp chamber wall, the measurement is performed at the moment of irradiation with a light pulse. The investigations for several low-energy measurements (1.5 -3.5 J) were performed using lesion reconstruction, the basic principle of which has been described in point 1. The selected initial real lesion was illuminated with a series of several (maximum 4.1-3.5 J) pulses spaced at 30s intervals. After illumination with the first pulse, the lesion was slightly darkened to simulate the original lesion. The irradiation energy E along the X-axis in figure 6 is the energy of the incident laser. Two ≈1.3-mm-thick samples of the tooth wall of the pulp chamber were used. On the left Y-axis, the temperature in degrees Celsius is given, increasing starting from room temperature ≈ 25^0C of the teeth studied. The right Y-axis shows the corresponding temperature for the actual situation with teeth in the human mouth - the increase at a mouth temperature of 36^0C. The high energy measurement ~3.5 - 5 J was performed for one or maximum 2 consecutive measurements - with a reconstructed lesion.

5. Discussion

From the measurement data shown in figure 6 can be summarized that the average increase in the pulp chamber wall temperature varies as (2-4.5)°C for an incident energy of ~ (1.5-2.6) J and an energy density of (40 to 70) J/cm^2; as (4.5-9)°C for E (2.6 -3.9) J, i.e. (~70-110) J/cm^2 and increasing to (9 -11) °C for E~ (4-5) J and energy density ~ 110 to 130) J/cm^2. Note that the plots presented in figure 6 are for the thickness of the combination of enamel and dentin here from the tooth surface to the pulp chamber Δd ≈ 1.3 mm. Our other measurements for a different thickness of Δd≈1.7 mm give for the incident light energy of 3.7 J a temperature increase to ~ 7°C, which is not so different from ~ 10.8°C that for a ~ 1.3 mm. Attention should be paid to the behavior of the resulting curve, especially after 3.5 J. For the microsecond light pulses, the chamber temperature does not increase linearly with the increase of the incident energy. The light in low-energy pulses takes longer to form a dispersion cloud,

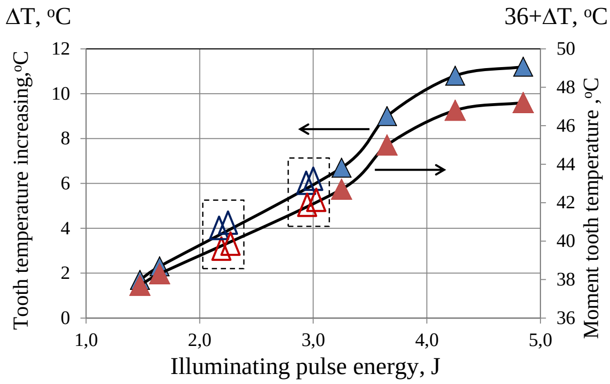

Figure 6. Increase in pulp chamber wall temperature T as a function of laser energy E(J) incident on the enamel lesion (≈ 2.1 mm diameter). The test measurement for two pairs of pulses of equal energy with lesion recovery with slight blackening are plotted in the two squares with dotted lines. Temperature measurement - according to the scheme and apparatus from figure 3, precision - 0.1 °C.

and therefore more light energy is involved in the heating and ablation process. At high energies, the main action and application of light energy is at the initial moment of the pulse, and the particles formed (plumes [1,2,6]) scatter higher energy than the initial high-energy part of the pulse. This qualitatively explains the nonlinearity (plots in figure 6) for the higher energies.

6. Conclusion

The results presented here concern the treatment of initial carious lesions with a small diameter of 1-3 mm using single pulses of Nd:Doped lasers (wavelength 1.064 µm). These lasers are one of the most widely used and available lasers for dental applications. The work shows that there are conditions for small, initial carious lesions (~ 1-3 mm) where such treatment can be effective and of potential practical interest. The required illumination energy, depending on the diameter of the lesion, can vary in the range of 1.2-4.5 J. It is important to note that the limit of laser energy at which the pulp chamber wall temperature, as found in the experimental studies in the work, does not rise more than the dangerous 11^{0}C, (~ 46^{0}C in the mouth, beginning of soft tissue necrosis in the pulp chamber). We also showed that treatment with the noted single pulse energy of ~1.5-3.5 J (energy density ~ 50-100 J/cm^2) allows good cleaning without crack [8] formation and preparation for the final healing procedure of the lesions (~1.5-2.5 mm in diameter). Despite the fact that the treatment of initial lesions of small size is not a typical case in dental practice, the presented results indicate the possibility of effective use of the discussed cleaning in some real cases - permanent control of a selected patient, including children.

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