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Applications of single laser pulse from Nd:doped lasers for cleaning of small diameter carious lesions. Modelling and analytical study

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Abstract. We report on an analytical study with physical modelling, some additional experimental studies and computer programming of the cleaning of initial carious lesions (1 - 3 mm in diameter) with a single laser pulse from Nd:doped (Nd:YAG and Nd:Glass) lasers (wavelength 1.06 µm). The analysis is based on experimental data from our preliminary study and aims to develop a method to predetermine the necessary laser pulse parameters for reasonable cleaning. To obtain such laser pulse parameters, we considered the conversion of light energy into heat, the propagation of incident light and the resulting heating of the dental tissue, the induced ablation processes associated with lesion cleaning, and the formation of the necessary hole in combination with acceptable heating of the pulp chamber and prevention of enamel crack formation. Cleaning is naturally associated with the bactericidal effect. The study, except for the estimation, confirms that the use of single light pulses of the considered lasers with energies from 1.3 to 4.5 J, densities from 40 to 120 J/cm^2, pulse duration from a few hundred microseconds to ~2 ms (i.e., in the simplest, natural, free mode of operation of the noted lasers) can be considered as a promising method to start caries treatment.

1. Introduction

Laser treatment of dental tissues is the subject of continuous research and development [1-7]. The goal of this work was to determine, by analytical treatment, the condition for safe cleaning of initial carious lesions (i.e. 1-3 mm in diameter) with a single light pulse of Ng:YAG and Nd:Glass lasers (Nd:doped lasers; wavelength 1.06 µm). Such a suitable cleaning capability has been demonstrated in our previous experimental work - by a single laser pulse from these lasers (energy 1-4 J) [1]. When the appropriate pulse parameters are selected, the desired cleaning removes the lesion, preparing the site for completion of the healing procedure. As is well known, these lasers also provide bactericidal cleaning [2,9]. Furthermore, for the cleaning noted, it is necessary to use energy that prevents unacceptable heating of the tooth, especially the pulp chamber [2-6], and does not cause the enamel cracks typical of high laser energy. Considering the known diameters of the lesions and adding some additional necessary data, the aim of the work is to use the developed modelling and programming to obtain the energy parameters of the laser pulses for the required complete and acceptable caries treatment. Based on our experise and review of the relevant literature, we focus on Nd:doped lasers. They have the potential to generate appropriately selected parameters to solve the noted problem. From a technical point of view,

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considering applicability, the lasers used in this work are among those considered suitable for dental applications [2-4,9], together with CO_2 gas lasers around 10 μm and Er^{3+}:doped solid-state lasers around 2.9 μm. These lasers have significant advantages-they are well designed, inexpensive, reliable, compact, and easy to apply, and importantly, they are suitable for combining into fiber-based medical devices. The effectiveness of lesion treatment is mainly increased by ablation of pigmented caries (natural, artificial) [3].

2. Selected objects for the study, beam parameters and experimental arrangement

Figure 1 presents selected illustrations from our experimental study in [1], necessary for consideration here, with a description in the legend. Some new necessary experimental measurements related to the parameters of the studied samples are additionally presented in figure 3. Light pulses are produced by the two noted lasers in their well-known natural mode of operation (Free Lasing FL mode, student's books, figure 1 (e) Nd:YAG laser pulses have a duration of ~500 μs and an energy of ~1-2.2 J.

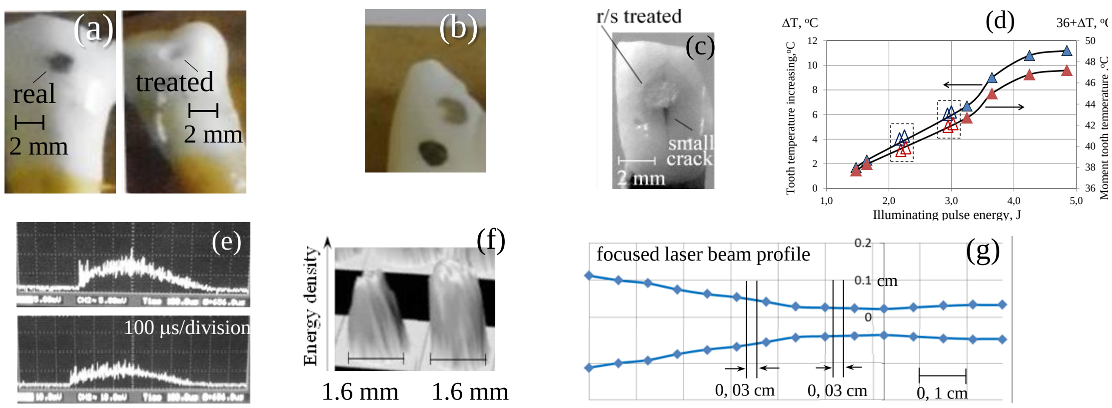

Figure 1. (a) left - real, initial carious lesion with a diameter of ~ 1.6 mm; right - good laser cleaning of a similar lesion after treatment with a single laser pulse (2.6 J, density ~ 120 J/cm^2; 0.5 ms) - conical hole formed with diameters ≈1.6 mm and ≈0.7 mm and depth ≈0.5 mm (Gaussian laser beam); a 12 cm focusing lens was used to align the beam and lesion diameters; (b) 1.5 mm simulated lesion, top - after treatment with light pulse of energy 2 J, ≈110 J/cm^2, (c) lesion 2.1 mm in size after treatment with 4.6 J, 110 J/cm^2 energy pulse (multimode laser); good cleaning, but with initial formation of crack; hole outer diameter 2.1 mm and bottom – 1.9 mm, depth ≈ 0.3 mm; (d) Experimental graph - increase in pulp chamber wall temperature ΔT as a function of laser energy E(J), left axis Y - pulp chamber wall ΔT, right axis Y - ΔT, starting from human mouth temperature of 36°C. Size of the irradiated lesion ≈ 2.1 mm; the temperature rise is measured after each pulse, with lesion suitably blackened before to approach the state at the first pulse; (e) oscillograms of the temporal emission in FL mode of the used Nd:YAG/glass lasers - for a pulse energy of 4 J (top) and 1.7 J (bottom); (f) spatial distribution of the energy density, according to our method of marking the spot on a special paper with additional computer processing [10]; 3D profile of the focused light pulses: left - for single-mode Gaussian laser beam, pulse energy 1.8 J, diameter in the base 1.6 mm; right - for multimode emission, pulse energy 3.2 J /1,8 mm; (g) The measured focused beam energy density near the focus. The focused light at a distance of ~1 mm is a parallel beam.

3. Principles of the used modeling and analysis. Tooth tissue parameters

The model used is based on the energy balance between the energy of the incident light beam and its conversion to heat, which is of interest for the pulp chamber wall. The calculations use the empirical-physical model [2,3,5], assuming that the chemical composition does not change, and only the phase change (solid-liquid, liquid-vapor) is considered. The schematic geometry of the consideration of light and heat propagation in tooth tissue from the surface to the pulp chamber wall is presented in figure 2.

First, it is necessary to calculate the light energy required to clean the lesion and to form a hole in its place. In order to calculate the temperature rise of the pulp chamber wall afterwards, the corresponding heating energy fraction is taken into account. The measured average loss due to initial reflection and scattering is ~10%. The remaining energy (active energy) heats the tissue and causes phase transformations and ablation of the tissue, discussed below. Of this irradiation energy, a fraction forms a hole and the remainder is scattered by the resulting plume of ablated particles. The scattering losses of the plume, following [11], can be assumed to be ~20% of the energy that forms the hole, with ~5% of it passing through the plume in the direction of the inner part of the hole as scattered directed light. The latter does not have enough energy and is not well focused, so it is unable to further increase the size of the hole. This part mainly heats the inner part of the hole and consequently heats the dentin column between the inner part of the hole and the pulp chamber wall, figure 2 (a). The studies reported in the literature are mainly for Er:YAG laser light, but the associated problems - scattered particle plume formation, losses and dispersion - are of a general physical nature and, with some approximation, can be assumed to be general for Nd:YAG laser light as well.

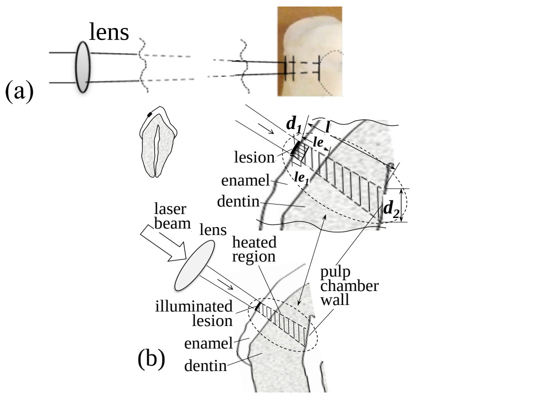

Figure 2. (a) illumination trough lense; (b) irradiation pattern and geometry of light and heat propagation in the tooth (to the pulp chamber wall); d_1=2.1 mm **(**in the considered case) - the front diameter of the hole formed in the enamel by incident light on the lesion; ℓ = 1.3 mm - the thickness (enamel + dentin) between the enamel surface and chamber wall, ℓ_e =0.35mm - enamel thickness, ℓ_{e1}=0.3 mm - depth of ablated hole; d_2 =2.3 mm - spot diameter on the chamber wall.

Figure 3. Photos: (a) spot with ablated hole on the enamel at the site of the lesion, diameter 2.1 mm; (b) tooth with the heat sensing element - the ball head of the system, for measuring heat in contact with the surface; (c) marked heated part on the pulp chamber wall after irradiation - diameter 2.3 mm; (d) inner cross-section of the irradiated tooth by appropriate cross-cutting of the tooth below the formed hole; the enamel and dentin are clearly visible (brighter and darker area).

In the analytical calculations we will take the tooth hard tissue parameters, mainly from the data in [2,3,6,11]. We also use some of our experiments - the enamel and dentin thickness studies in the healing position of the tooth. Our measurements are performed by cutting the tooth sample along the diameter figure 3, the treatment site. It should be noted that the combined thickness of enamel and dentin and the ratio between their thicknesses vary at different points on the cross-section of the tooth, clearly seen in figure 3(d). In this way, we can verify the correctness of the computational model for the selected tooth cutting case. For such complex and variable materials as the human tooth, tooth parameter maps for human tooth structures and parameters for different ages and regions should be noted (at least averaged).

4. Modeling and analytical description

Let us calculate the energy to form the hole in the tooth enamel for the case considered in figure 1 (a): a truncated cone with diameters 1.6 mm 0.7 mm (inner) and depth 0.5 mm. The volume of the hole, formed and ablated enamel is 5.46×10^{-4} cm^3. For an enamel density of $\rho = 2.8$ g/cm^3 the mass of the ablated enamel is $m_{en}=\rho \times V_h=1.5 \times 10^{-3}$g. The energy to heat the enamel to the melting temperature T_{en_melt} is $E_{en\_heat} = m_{en} \times c_{en.p} \times \Delta T$, where $c_{en.p} = 0.71$ J/g.°C is the specific heat of the enamel, and $\Delta T \approx T_{en\_melt}$ is given by the difference in heating, which starts at ~25°C and rises to T_{en_melt} = 1280 °C or T ≈ (1280°C - 25°C). Thus we obtain for the energy to reach the melting point of the enamel $E_1=E_{en\_heat}$ =

1.28 J. The energy E_{en_melt}, which melts the enamel, is $E_{en\_melt} = L_{en\_melt}$ x m_{en}, where the latent heat is L_{en_melt} = 200 J/g or E_2= E_{en_melt}=0.31 J. Thus, the energy required to prepare the enamel for ablation is 1.59 J. The mass of water is m_w = 0.04 x m_{en} or m_w = 6.3x10^{-5} g. For the energy related to the contribution of water to the ablation, the following three components are relevant - the energy E_{w_vap} to heat the water to the evaporation temperature, which gives E_{w_vap} = m_w x c_{pw} x 100ºC = 0.026 J with a specific heat of water c_{pw}=4.18 J/gºC. The second component is the latent heat of vaporization of water, which is $E_{w\_lat\_vap}$ = m_w x L_{w_vap} =0.14 J for the latent heat of vaporization of water L_{w_vap} = 2260 J/g. The third component is the energy $E_{w\_heat\_enam}$ for heating the evaporated water in the enamel to the enamel liquid phase conversion temperature i.e., from 100ºC to 1280ºC. The heating of the water is not uniform throughout the process, and as a reasonable approximation we assume the average temperature of ½ x (1280 ºC – 100 ºC) - i.e., 590ºC. The energy to heat the superheated water vapor to this temperature is Ew_heat_enam = m_w x c_{vh} x [½ (T_{en_melt}-T_{w_vap})], which gives $E_{w\_heat\_enam}$=0.067 J at heat capacity c_{vh}= 2 J/(g.ºC) of water vapor. Thus, from the given calculation of the energy to clean the lesion and to form a hole with outer and inner diameters of 1.6 mm and 0.7 mm and a depth of 0.5 mm, the total energy is given by the sum $E_{en} = E_{en\_heat} + E_{en\_melt} + E_{w\_vap} + E_{w\_lat\_vap} + E_{w\_heat\_enam}$ of the calculated energies. This gives the required light energy of 1.81 J. After accounting for the 20% scattering losses from the ablated particles, we get 2.2 J. Adding 5 % (0.11 J) losses from scattering and reflection of the initial light irradiation on the lesion gives a theoretical energy of 2.26 J (~110 J/cm^2) to clear the lesion to form a hole with the parameters given above. The total energy to clean the lesion and to form a hole is 1.81 J. After accounting for 20% scattering losses and adding 5% (0.11 J) scattering and reflection losses of the primary light, the theoretical energy is 2.26 J (~110 J/cm2). The experimentally obtained energy is 2.6 J, i.e., the difference is ≈ 0.3 J or ~15%, which can be considered a realistic value given the variety of parameters used and of the teeth. The main ones used here are based on [2,3,6,11].

Case 1			**Case 2**								**Table 1.**
d_1	**0,16**	cm	d_1	**0,21**	cm	ρ	2,8	g/cm^3	$c_{en.p}$	0,71	J/g.ºC
d_2	**0,07**	cm	d_2	**0,19**	cm	T_{start}	25	ºC	$c_{p.w}$	4,18	J/g.ºC
h	**0,05**	cm	h	**0,03**	cm	T_{en_melt}	1200	ºC	c_{vh}	2	J/g.ºC
V	0,0005	cm^3	V	0,00094	cm^3	ΔT	1175	ºC	L_{en_melt}	200	J/g
m_{en}	0,0015	g	m_{en}	0,00264	g	4 % *of water mass*			L_{w_vap}	2260	J/g
E_{en_heat}	1,28	J	E_{en_heat}	2,203	J	energy for heating the enamel to 1280 ºC					
E_{en_melt}	0,31	J	E_{en_melt}	0,528	J	energy for melting of the enamel					
m_w	6,1x10^{-5}	g	m_w	0,00011	g						
E_{w_vap}	0,026	J	E_{w_vap}	0,044	J	energy for vaporisation of water					
$E_{w\_lat\_vap}$	0,138	J	$E_{w\_lat\_vap}$	0,239	J	latent heat of vaporisation					
$E_{w\_heat\_enam}$	0,067	J	$E_{w\_heat\_enam}$	0,116	J	20% losses in plume			**5%** refl., scatt.		
ΣE_w	0,231	J	ΣE_w	0,399	J			3,90 J		15% diff.	
E_{total}	**1,81**	J	E_{total}	**3,13**	J	E_{heat_dentin}= 5% of 3,13 J = 0,16 J					
$d_{1dentin}$	**0,07**	cm	$d_{1dentin}$	**0,19**	cm						
$d_{2dentin}$	**0,25**	cm	$d_{2dentin}$	**0,21**	cm						
h_{dentin}	**0,2**	cm	h_{dentin}	**0,1**	cm	C_{pd}	1,6	J/g.K			
V	0,0054	cm^3	V	0,0042	cm^3	ρ_d	2,1	g/cm^3			
m_{dentin}	0,01	g	m_{dentin}	0,0088	g						
E_{dentin}	**0,09**	J	E_{dentin}	**0,15**	J	the energy that heats the dentin					
ΔT_{dentin}	5,03	ºC	ΔT_{dentin}	11,01	ºC	heating of the dentin after ablation of enamel					

The analysis of the heating of the pulp chamber wall - the increase of its temperature, is done on the example given in figure 3, where between the lesion and the pulp chamber wall are the two layers of enamel and dentin, as seen in figure 3 (c). The hole formed at the site of the lesion is ≈2.1 mm outer and 1.9 mm inner in diameter with a depth of 0.3 mm. The hole was completely in the enamel and, using the detailed approach described above, we have calculated the energy required - of 4.7 J to clean the lesion with the hole formation. At the site of the lesion, after treatment, we cut the tooth lengthwise, halfway through the hole - figure 3 (c). In this way we measured the thickness of enamel and dentin - 1.3 mm in total, 0.35 mm for enamel and 0.95 mm for dentin. Of the 4.7 J energy for hole formation, ~5% illuminates and heats the bottom of the hole, the start of the dentin layer, and the latter is part of the pulp chamber wall. Thus, its heating and increased temperature are for the portion of the chamber wall that is the subject of our study. Calculating in the same way, we obtain that the part of the dentin layer starting from the bottom of the hole has increased by 11°C, or this temperature increase of the pulp chamber wall at the hole site (black spot, figure 3 (c)) is acceptable. We programmed the presented basic steps with heating of the pulp chamber wall. The parameters, calculation sequence and results are presented in table 1. A generalized evaluation, as an example, for heating of the entire tooth for a laser pulse energy of ~4-5 J and several hundred microseconds duration, at a tooth length of ~12-14 mm, is ~8ºC-10ºC, versus ~1200ºC for the carious area with a depth of ~0.3-0.5 mm leading to the ablation. The measurement also gives an estimate of the heat penetration lengths at different illuminations.

5. Discussion and Conclusion

We develop modeling and programming of an initial lesion (1-3 mm diameter) for cleaning with a single pulse of Nd:Doped laser. The program has to introduce the diameter of the lesion and its location in the teeth and gives the necessary parameters of the pulse for cleaning with creating the necessary hole with treatment completion.The program also gives the temperature of the pulp chamber wall which is increased. The studies are for well developed, widely available and well adapted Nd-doped YAG and glass lasers (operating wavelength 1.06 µm; free laser emission with microsecond pulses). We show that single laser pulses from with appropriately selected parameters in the range of 1.5 J - 5 J provide in a very short time the treatment process - cleaning of the lesion, formation of a suitable, bactericidal cleaned hole for placing the polymerizing compound paste and with accessible heating of the pulp chamber wall. The problem for the widespread application of the technique is that it is also necessary to know the parameters of the tooth (in many cases this is the knowledge of the dentist). A solution for future application of the developed methodology is the application of tooth parameter maps for different ages and specific regions. The application can be related to continuous monitoring (almost every week) of the teeth of a selected patient, including especially children. This allows for the future development of equipment for a computer-controlled and operative laser-fibre-optic system, similar to laser techniques used in eye treatment.

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