COMPOSITE LASER SPOT USE FOR HARD TISSUE PROBLEMS TREATMENT IN THE DENTAL MEDICINE – NEW TECHNOLOGY, ANALISIS, APARATUS AND TEST

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Abstract

We develop and present here important details of proposed by us principle for improvement of enamel caries treatment using spatially formed high power laser pulses. We give the principle, the approach for calculation of the needed spatial shape of illuminating radiation with corresponding energies and describe the experimental test. Considered is a specially developed by us patented laser on the base of Nd:YAG active medium. The laser provides composed spot with annular external and circle internal light each with conveniently chosen energy and time characteristics. Such formed pulse illumination assures, except for the caries lesion cleaning in given condition, the strong decreasing of the temperature gradient built in the treated enamel area and respectively permits to avoid the neighbouring enamel bursting.

1. INTRODUCTION

The application of the high power/energy laser radiation for treatment of caries or other defects in hard tooth tissues is considered as a perspective procedure [1]. Increasing the energy parameters of the operating light facilitates and allows effective treatment of the hard dental tissue. However, due to general reasons, especially due to non-homogeneous heating of the tooth tissue, this can lead also to tooth damage. The aim of this work is to present the development of the introduced by us idea for improvement of such treatment with corresponding calculation and preliminary experiments and the developed laser source on the base of our patented principle to use a complex laser spot. The laser with specialised coaxial two-beam geometry provides composed spot with annular external and circle internal light each with conveniently chosen energy and time characteristics. Such formed pulse illumination assures, except for the caries lesion cleaning, the strong decreasing of the temperature gradient in the treated area and respectively permits to avoid the strongly no desired neighbouring enamel cracking.

2. THE PROBLEM, THE PROPOSED PRINCIPLE, ANALYSIS AND LASER FOR SOLUTION

Principle and analysis

During our previous study of the processes of high energy density laser light treatment of tooth tissues [2,3], we have clearly observed the problem of enamel crack when the tooth surface is treated with high energy density laser light. From the general and well clear physical reasons, the problem via high energy and short time duration pulses using (typically employed) can be related with appearance of high temperature gradient that creates the mechanical tension, combined with the heated volume expansion. The laser illumination, typically of few hundred and less μs and respectively without the heat dissipation, increase the temperature of the treated area to many hundred degree against the few tens degree of the surrounding enamel. Both non-desired effects – tension and volume expansion, are essential factors for the crack formation.

Our experimental observation and measurement, for practically realized by us condition, show that when the laser illuminating energy E ~ 1 J is focalized in a spot with diameter of D ~ 0.7 mm (~ 150 J/cm^2) on the carious lesion, there is a strong ablation, accompanied with the fire filament in depth of the tooth of d ~ 0.1 mm. In our analysis we will consider the case of small area enamel surface lesion. Using the noted dimensional data and the enamel thermo and physical parameters we can calculate the temperature increasing in the treated lesion. Our study shows that the variation of the characteristics of the same type of tooth is so large, that we can speak only for 'evaluation", i.e. with a precision in the order of 50 – 70 %. The question of this type of analysis is very complicated and has, generally speaking, the character of the qualitative discussion with some reasonable estimation. Part of the needed enamel thermo and physical parameters we take from the literature [4] and other – from our proper experimental investigations. We collected for the enamel the following series of data: mass density (ρ_e) of 2950 kg /m^3, thermo-capacity (C_{ec}) of 970 J/kg.K with thermal conductivity (H_{et}) of 0.79 W/m.grad [4]. The other parameters – the latent heat of fusion (L_{ef}) and of vaporization (L_{ev}) can be taken to be as the one for some other materials that show thermic behaviour like this one of the enamel. For example, here we can note the steel and iron. For the same illuminating energy density (pulse energy, focal spot) and duration we obtain for these materials the formation of similar holes as this one in enamel. Thus, on the base of this not so strong reason, we can accept the latent heat of the fusion (L_{ef}) and the vaporization (L_{ev}) of the enamel to be no strongly different from these ones of the steel– i. e. in the order of 2.5x10^5 J/kg and 6x10^6 J/kg respectively. We accept also that the small caries lesion has approximate parameters such as the pure dentin – as these ones, noted before. From our measurement we found the coefficient of the reflection for the interesting wavelength of 1.06 μm. For the pure enamel the reflection was as the one from a convex spherically like mirror with strong diffusion component. In the measurements we have focused the reflected light with convenient lens. We found that the reflected light is in the order of 20 % (averaged; R_e ~ 20 %) and strongly varied from teeth to teeth (10 to 25 %). For the carious lesion the reflection also was definitively variable for the different lesions with diffusion character and of order to 3 – 10 % (R_l). Note also that due to the low thermal conductivity of the enamel (~ 0.7 W/m.^{o}C [4]) the heat energy cannot be dissipated and increases the temperature of the treated area.

The given approximate values showed in the previous paragraph can be still practically used for estimation of the temperature rising in the treated enamel carious lesion (averaged, typical) and of the pure enamel. Thus, for the considered spot, after some clear physical calculations (applied the composed formula (1)) we obtain that the temperature of the treated area, during the laser pulse and before the ablation, increases to be about 1400 - 1700^{o}C.

$$\Delta T = \left[E(1-R_e) - (L_{ef} + L_{ev}) \cdot \left(\pi \frac{D^2}{4} d \cdot \rho_e \right) \right] * \\ * \left[C_{ec} \cdot \left(\pi \frac{D^2}{4} d \cdot \rho_e \right) \right]^{-1} \qquad (1)$$

where the used notations in (1) are given in the text.

The temperature of the lesion surrounding enamel rests as of this one of the human body of ~ 36^o C (for the case of absence of external heating illumination). It is reasonable that such very high temperature gradient provides high thermo-elastic tension and respectively formation of the compromising the laser treatment cracks in the enamel. As addition, the appearance of such cracks is favoured by the structural transformation for long time illumination (~ 20 s, ~ 0.1 J in the pulse) and probably by enamel melting (after 1000 ^{o}C) [4]. We will accept that for our conditions the main reason for the cracks appearance is the mechanical tension as a result of the high temperature differences (our proper observation, also from the literature [4]).

Our experiments clearly show existing of the crack problem. In Fig.1 are shown photographs of teeth after enamel lesions treatment with high energy laser light ~ 150 J/cm^2 (focalized E ~ 0.8 \ J on the area of ~ 0.7 mm diameter, the used by us laser pulses with duration of 0.1 to 500 μs).

This energy density is convenient for enamel lesion cleaning. However, from the photograph, the formed cracks are clearly evident. Such cracks increase constantly with time and finally destroy the tooth.

Our experimental investigations show that for acting on the caries lesion and enamel with low laser light energy density (less than ~ 80 J/cm^2) the cracks do not appear. However, the treatment (lesion cleaning) is not effective.

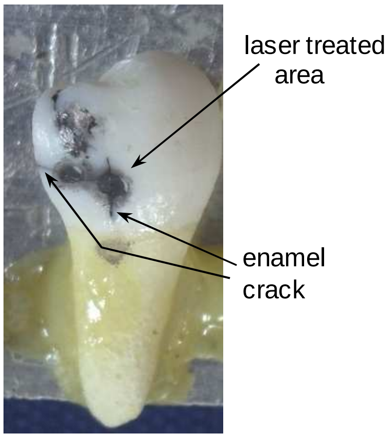


Fig. 1. Photograph of the dental caries on the enamel lesion after treating via focalized microsecond duration laser pulse with energy of 0.8 J (energy density ~ 150 J/cm^2). The formed cracks in the enamel can be seen.

The idea for elimination of the essential problem with formation of cracks is to strongly reduce temperature gradient formed in the enamel operating region. For realization of this idea we have proposed and developed, on the base of our patented principle [5], a special pulsed laser, in our case with most commonly used Nd:YAG active media. The solution of the laser permits to be produced convenient composed beam for eliminating of the crack problems. On the base of application of our two coaxial channels geometry, the laser emits the complex beam, formed by the annular external part and in the bore axially disposed internal circular beam. The beam cross section of our laser is shown in the photograph in Fig. 2

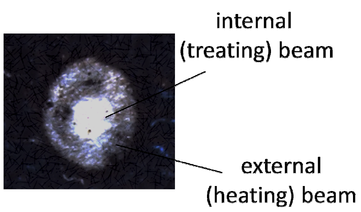


Fig. 2. The beam cross section of our laser - photograph

3. ANALYSIS

The parameters of each beam are independently controlled - energy, duration, wavelength. In this laser it is easy to form spot with external annular light that assures heating of the enamel surrounding of the treated lesion to the high temperature, however lower than this one for the cracks formation (~ 800 ^{o}C). The internal beam for efficient treatment, heated the lesion to the noted 1400 - 1700^{o}C. However, now the temperature difference between lesion with high temperature and the surrounding decreases low than the difference for the crack formation. On the other hand, the temperature of the heated surrounding is less that this one, causing the cracks and thus the cracks formation is avoided.

Taken the discussed already approach for calculation; we can obtain the expression for calculation of needed energy in the annual part that permits to heat the lesion surrounding to the needed temperature. The calculations are identical to these ones given by the formula (1) but without the terms describing the fusion and vaporisation and take into account annular spot surface with approximately the same heating depth as for treatment with central spot.

4. EXPERIMENTS

Our experiments, described below, confirm well the usefulness of the developed technique and the convenience of the developed apparatus.

4.1. Laser apparatus description

As a first point, a short technical description of our coaxial geometry laser will be given. More detailed description is given in our recent work [6]. The optical scheme of the laser is presented in Fig. 3. For the advantageous realization we use low-Nd^{3+}-doped (in our work ~ 0.5 at %) Nd:YAG crystal. Such doping, instead of typical ~ 1 %, is also commonly used and assures sufficient efficiency of the generation in combination with high quality of the output beam. The cylindrical YAG rod (diameter Ø = 0.7 cm and length l = 8 cm) was with silvered envelope wall. Our study shows that a laser active element with the given parameters assures a notable focusing effect in the axial region, resulting in an increase of ~ 2½ times for the pump power density in the near axial rod part. In the experimental arrangement, the laser rod was in a close position with a pump flash-lamp in a commercial pump-chamber with UV-absorbing quartz elliptic cylinder-pump light concentrator (by silvered walls; axes 23 x 29 mm, length 78 mm) and with holes for the laser rod and the lamp of ∅ 9.5 mm and 11.5 mm. The lamp (IFP 1200 type, 700 Tor of Xe, ∅ 0.95 cm, Russia) and the crystal were surrounded with cooled flowing water at temperature 18 ± 0.3 ^{o}C. The electrical supply was standard, homemade, providing electric energy from 70 to

160 J in ~ 400 µs FWHM lamp pulse duration (at 1 Hz repetition rate). Typically, we have used as pump energy of 140 J.

The light generation at two beams was achieved in two, coaxially arranged and optically separated parts of the Nd:YAG laser rod, each equipped with its own 40 cm length resonator (hatched differently in Figure 2 (a)). The optical separation is realized using a rectangular separating prism SPr with a hole (in our experiment with 3.7 mm diameter, length of 4 mm) through the cathetus and the hypotenuse. A thin metal tube with ~ 0.12 mm thick walls and 30 mm length was introduced in the hole. The external part is coupled with its resonator by reflection of the SPr outside the hole. The described prism separator assures very good formation of both spots.

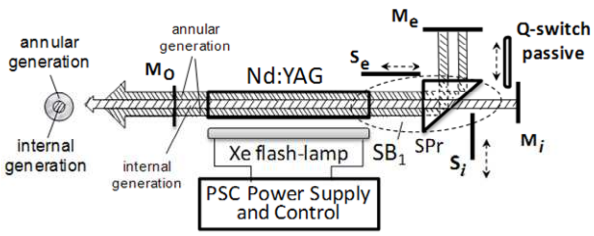


Fig. 3. Scheme of the developed two-coaxial beam emitting Nd:YAG laser, using as separator of the channels a prism SPr with a hole and selective-flat mirror resonators. The passive Q-switch is Cr^{4+}:YAG plate with convenient parameters

4.2. Experimental test

In our work, we have experimentally illustrated the use of our described two-channel laser, the ideology of the composed beam and the given approaches for laser beam parameters estimation. For the test we investigate the small surface laser lesions on the enamel (diameters ~ 0.7 – 1 mm). This permits the usage of focalized laser beam for treatment. We found that the effectiveness of the laser action increases essentially if the treated area of the enamel by the laser was slightly marked with black pencil. The corresponding energy is estimated by expression (1). For our condition of the treated small area lesions (diameters of ~ 0.7 mm) we have estimated the laser treating beam energy to be ~ 0.7 J (energy density ~ 150 J/cm^2). This provides temperature increasing in the treated area up to ~ 1700 ^{o}C. The heating beam has external diameter of 1.5 mm and internal one of 0.7 mm. The needed energy was estimated to be ~ 0.3 J assuring increasing of the temperature to ~ 700 ^{o}C.

With our laser, described already in Sec.3.1, we easily have realized these requirements. The principle of the technical realization via laser beam focalization is shown in Fig. 4 (the picture). With stopped heated beam (external beam) we, as a rule, have obtained the effects of enamel cracking around and in the treated area, as it is shown in Fig. 1. The crack traces on the enamel is clearly evident.

When the laser produces the complex beam with the described parameters, no cracking was noticed. In Fig. 5 is given the photograph of the tooth after treating via focalized laser light. Note that to improve absorption by the caries we have coloured the illuminated tooth's surface with appropriate very thin black dye layer.

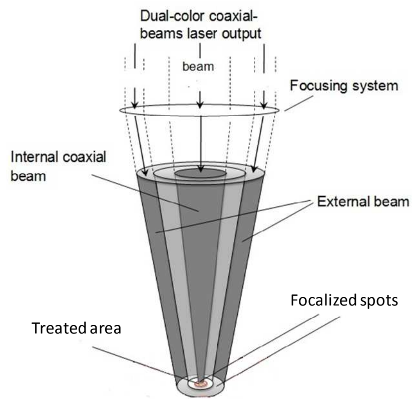
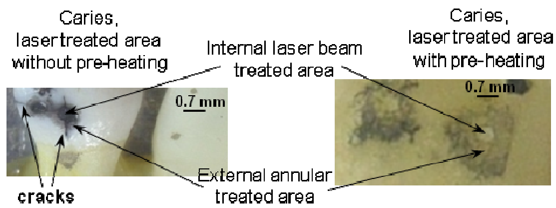


Fig. 4. Scheme of the technical realization via laser beam focalization



(a) (b)

Fig. 5. The photograph of caries treated area with direct illumination with a Q-switched pulse (a) and with annular illumination before high power pulse; (b) – no trace of crack can be seen

5. CONCLUSION

In the work we have reported the important details of proposed by us principle for improvement of enamel caries treatment using spatially formed high power laser pulses. The developed formed pulse illumination, assure, except for the caries lesion cleaning in given condition, the strong decreasing of the temperature gradient built in the treated enamel area and respectively permits to avoid the neighbouring enamel bursting. We give the principle, the approach for calculation of the needed spatial shape of illuminating radiation with corresponding energies and describe the experimental test. The used Nd:YAG laser for the experimental test, specially developed by us on the base of patented principle, is shortly described. Generally speaking, as we have noted already, that the phenomenon of cracking vary essentially with the teeth treated, especially the laser energy density and power. This is related with the treated teeth property variation. However, the proposed solution for the cracks formation avoiding can be generalised with the chosen convenient combination of the complex light beam parameters for lager assurance of the positive action. This is the problematic of our future work.

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