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THERMAL MEASUREMENTS FOR THE INVESTIGATION OF LASER PULSES EFFECTS ON HUMAN TEETH.

Paolo Castellini
Gian Marco Revel
Lorenzo Scalise
Università di Ancona, Dipartimento di Meccanica,
60131 Ancona, Italy

Abstract. *Thermal effects caused by Nd:YAG laser pulses (532 nm) on human tooth surface are investigated using an infrared high frame rate (60 Hz) detector (256x 256 elements, Indium Antimonide, with 3-5 μm spectral bandwidth). Measurements of the temperature on the tooth surface during exposure to laser pulses of 50 mJ of energy, with time amplitude of 12 ns and 10 Hz of frequency repetition are performed. Images and maps of temperature of the human tooth surface are shown during laser treatment. Results are discussed with particular reference to the possibility to evaluate thermal effects of pulsed lasers of frequent use in dentistry and to the application of such lasers as excitation sources for non-destructive defect analysis of human teeth by laser Doppler vibrometry.*

Keywords: *Teeth, Laser Doppler Vibrometry, Laser Pulses, thermal measurements.*

1. INTRODUCTION

The use of optical measurement techniques is becoming very frequent in many engineering and non-engineering applications. Non destructive Testing (NDT) is one of the research fields where optical techniques have been widely employed. For example, the possibility to detect the presence of defects inside structures, as fresco paintings, icons and composite materials using a Laser Doppler Vibrometry (LDVi)[1,2] based procedure, has been demonstrated in [3 – 5] and on-field applications are actually working[6].
Also the medicine field has demonstrated great interest in non contact optical techniques, because of their ability to quickly provide a significant amount of data, extremely useful for the diagnosis and prognosis of many phatologies.
Research is now proposing new procedures, techniques and methodologies able to improve the quantity and the quality of the data to be analysed by scientists. From this point of view, optical techniques seem to be very promising. In particular the possibility to measure without target contact is of extreme importance especially in medical applications. In particular, the absence of contact guarantees hygiene of the procedure and in some cases it may result fundamental for the use with biological tissues. For example, if the human skin is the measurand, it becomes clear how the elasticity of the human tissues makes impossible the use

of any other sensor than optical ones.
In recent years, Laser Doppler Vibrometry (LDVi) has demonstrated its capability of performing such investigation in particular areas of medicine[7-15]. Otholaringology, in particular is one of the areas of medicine where LDVi has been applied with great success. Many different applications of LDVi have been studied and in-vitro and in-vivo tests have been conducted [7 - 10].
Dentistry is one of the other medicine fields where LDVi have found possibility of applications[11-15]. In [11-13] human teeth mobility has been measured in-vitro and in-vivo using an impulsive excitation of the tooth (by an instrumented hammer) and measuring the consequent displacement by LDVi. The measured oscillations of the tooth have been used to characterise the human teeth mobility. This procedure has been tested in-vitro and in-vivo.
In [14] the possibility to investigate the frequency behaviour of human teeth has been studied, a procedure for the measurement of such properties has been individuated and in-vitro tests on human teeth have been conducted. In [14] the possibility of overlapping the human teeth resonance frequencies with excitation frequencies of devices used in dentist practice, such as ultrasound or air-compressed drills, has also been demonstrated.
In [15] authors have presented a procedure for the individuation, by LDVi analysis of the vibration behaviour of teeth structural modifications (cavities, micro-leakage’s or fractures).
Both the procedures presented in[14] and in [15] are based on the measurement of teeth vibrations using a laser Doppler measurement technique (LDVi, Laser Doppler Vibrometry), vibrations on teeth are induced by laser generated pulses focused on their surface. The selection of this kind of excitation was induced by the characteristics of the human teeth. Small dimensions, reduced weight and high stiffness, in fact, make the use of classical excitation techniques, such as shakers or impact hammer, impossible. An analysis of the performances of laser pulse excitation has been conducted in [16-20]. A comparison between laser pulse excitation and hammer excitation on mechanical target has been conducted in [21]. In the present paper, authors study the effect of Nd:YAG laser pulses in terms of thermal effects.
Data collected in this paper should allow to clarify the degree of “intrusivity” of such kind of excitation source. It is, in fact, important to determine what is the thermal effect on human tooth when it is exposed to a Nd:YAG pulsed radiation. From these investigations it should be possible to estimate the maximum exposure time, before thermal effects can individuate permanent damages. Indications from this paper could be used to optimise the use of different laser sources and to select working parameters such as power level, repetition rate and time duration of pulses.

2. MEASUREMENT PROCEDURE

The experimental arrangement used for this investigation is shown schematically in Figure 1. The excitation source used to excite the tooth is a Nd:YAG laser source. It is focused at 1 m onto the human tooth surface. The laser pulses produced by this laser source are of 50mJ of energy, they have a pulse time duration of 12 ns and the pulses repetition frequency is of 10 Hz. The level of power for the laser pulses has been selected on the basis of the data presented in [16]. In[16], a series of vibration power spectra of human tooth, excited by laser pulses generated at 532 nm by the same Nd:YAG source with a energy level ranging between 65 and 110 mJ per pulse, was measured. It was shown that 50 mJ was the minimum energy level necessary to obtain vibration spectra with sufficient high S/N ratio. Therefore all the tests presented hereafter have been conducted using a power level for the laser pulses of 50 mJ of energy. The tooth has been blocked on a special support of resin that keeps the tooth firmly fixed during the test.

The infrared camera used to measure the thermal effect of laser pulses on the tooth surface is a Amber Radiance 1. It is equipped with an FPA detector composed by 256 x 256 InSb (Indium Antimonide) sensors.

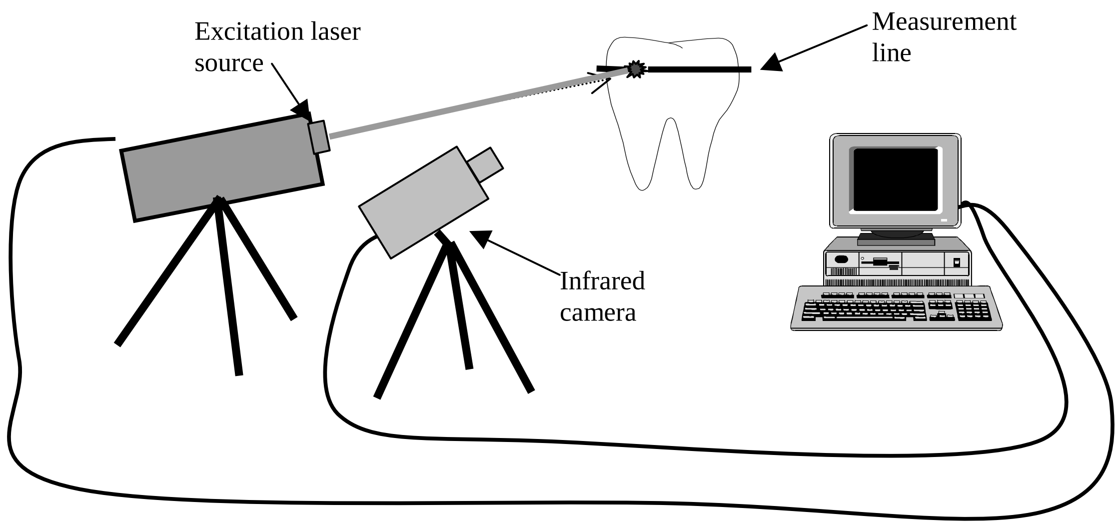


Figure 1 - Schematic of the experimental arrangement.

The detector maximum available frame rate is of 60 frames per second (60 Hz) and the spectral band is 3–5 μm, the NEΔT (Noise Equivalent ΔT: 0.025 K). The camera is connected to high-speed acquisition board, with 12 bits of resolution. The acquisition board is used to control the beginning and the duration of the Nd:YAG pulsed emission. The calibration of the infrared sensor was conducted measuring four temperature points on the surface of the tooth measured using a thermocouple. The uncertainty in the temperature determination by infrared termography can be evaluated to be about 1÷1.5 °C over the whole measurement surface. This value is estimated by taking into account the accuracy in the measurement of the reference temperature (performed using a thermocouple) and the interfering input due to the curvature and to the non-uniformity of the measured surface, which can induce a variation in the observed emissivity.

3. RESULTS.

In what follows the results obtained with the test set-up reported in Figure 1 are reported. For all the results reported hereafter the laser pulses repetition frequency was 10 Hz and the power of laser pulses was 50 mJ.

In Figure 2, the temperature along the horizontal measurement line, its position respect to the measured tooth is reported in Figure 1, is reported. The line is composed by 40 temperature measurement points. The 12^{th} point is the one on which the laser pulses radiation is focused on. Figure 2 reports the temperature measured along the line during a laser pulses exposure of 2.8 s. Fifteen measurements have been performed with a time step of 0.16 s.

The temperature along the line during an exposure of 8 s is reported in Figure 3. In the first 8 s of exposure a maximum temperature of 37.2 °C was measured after 6 s.

Figure 4 reports the temperature of the measurement line during an exposure of 22 s. For this Figure the time step was of 2 s. A maximum temperature of 40.5 °C was reached after 22 s on the measurement point number 12 (in the x position). A temperature increase after 22 s was of 16.3 °C. The thermal decrease after an exposure of 10 s corresponding to 100 laser pulses was measured along the measurement line. Results are reported in Figure 5. A maximum starting temperature of 35.4 °C, after 10 s the temperature on the same point was of 27.2 °C: the thermal decrease was of 8.2 °C, was measured.

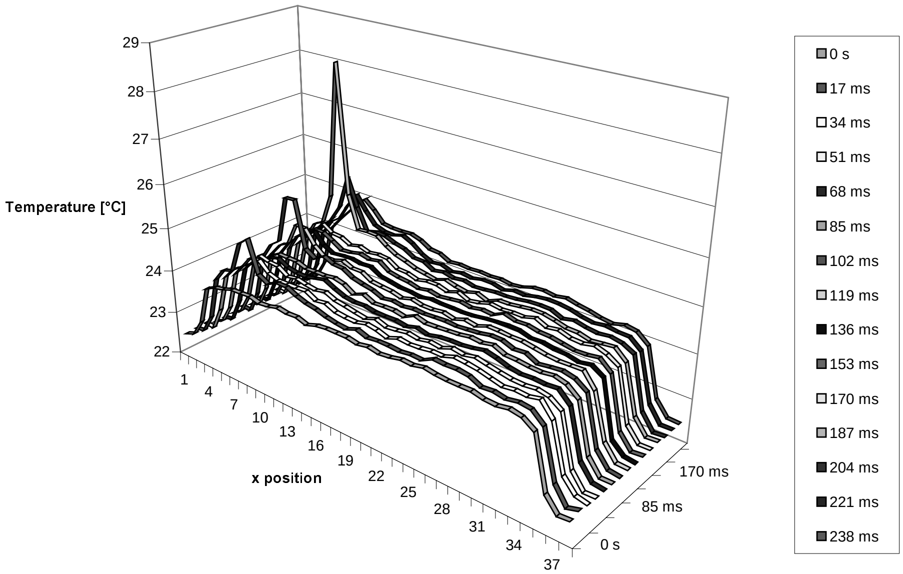


Figure 2 - Temperature measured along the measurement line (observation time: 0.238 s).

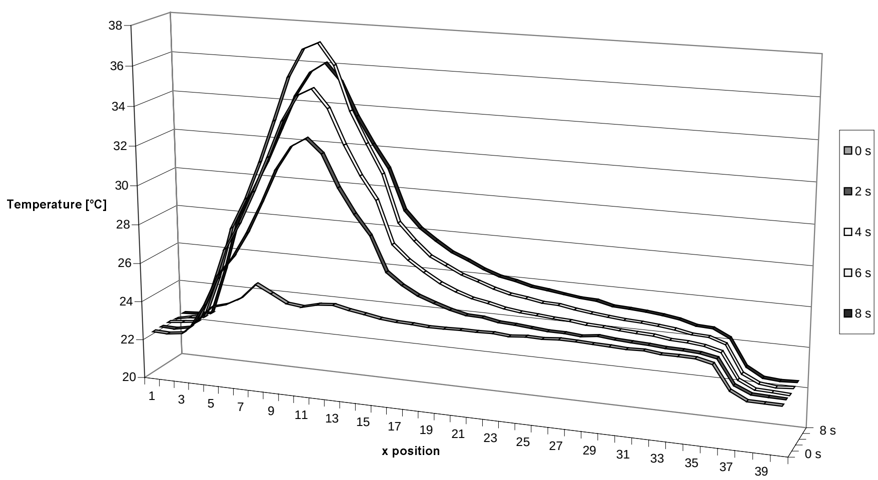


Figure 3 - Temperature measured along the measurement line (observation time 8 s).

The temperature on laser pulse incidence point (position number 12 along x-axis of Figure 2) on a time interval of 0.238 s, is reported in Figure 6. Starting temperature was of 24.0 °C. The first pulse increases the temperature up to 25.2 °C. The second pulse increases the temperature of 0.4 °C reaching 25.6 °C. With the third pulse a temperature of 28.3°C was measured. A temperature increase of 3.8 °C was measured in 0.017 s (measurements between 0.17 s and 0.187 s).
A temperature decrease on a time window of 2 s is reported in Figure 7. A temperature decay of 5.2 °C was measured. Respect to Figure 5, Figure 7 has been realised using a time step between the measurements of 0.1 s.

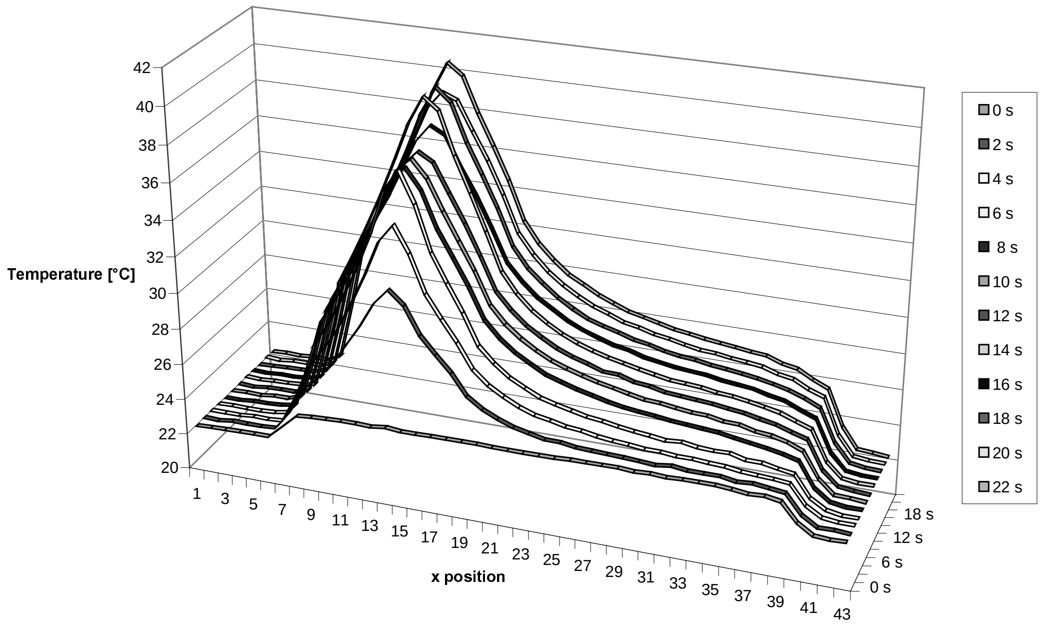


Figure 4 - Temperature measured along the measurement line (observation time: 22 s)

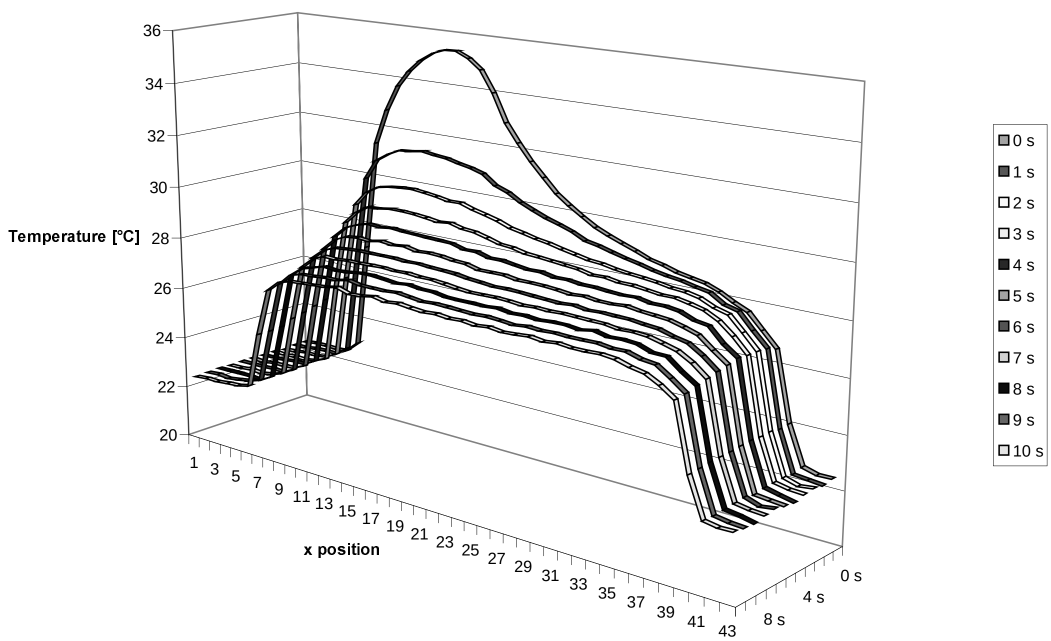


Figure 5 - Temperature decrease along the measurement line after 1 minute exposure (observation time 10 s).

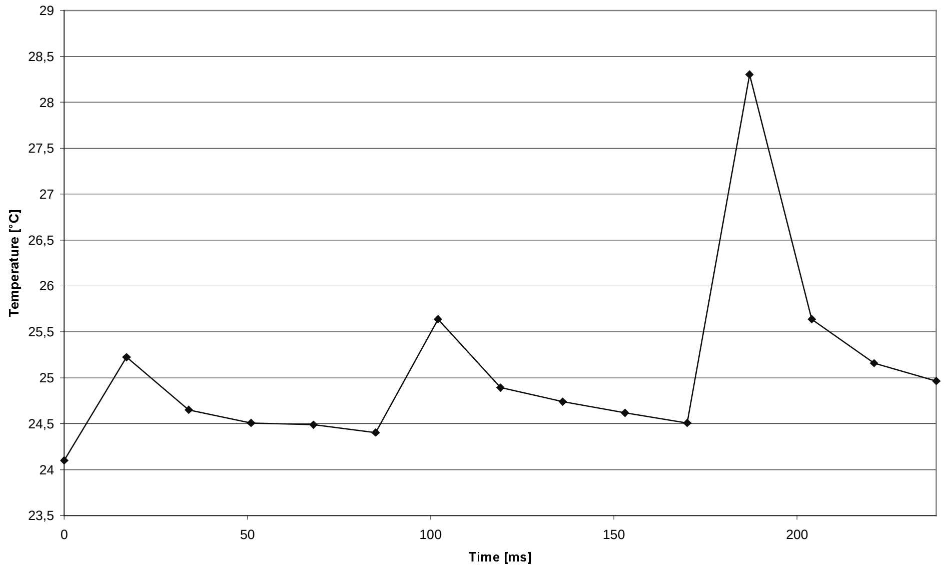


Figure 6 - Time history of the temperature on the laser pulses incidence point.

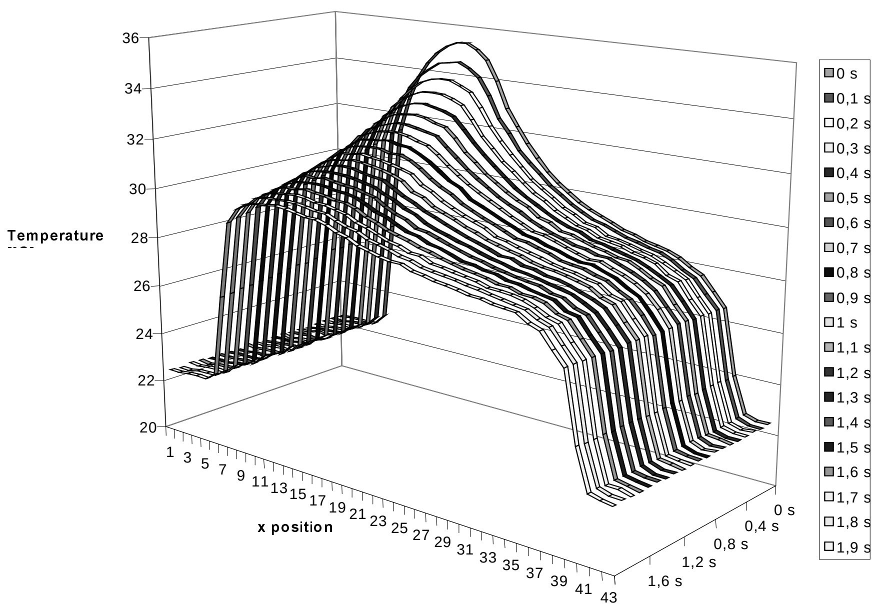


Figure 7 - Temperature decrease after a 10 s of laser pulses exposure (time step between measurement: 0.1 s).

4. ANALYSIS OF RESULTS.

The results here presented can be used to determine the thermal properties of the tooth, which are considered important from the medics.
The temperature under the exposed surface of the tooth can be expressed, in first approximation, with the expression[23]:

$$T(z,t) = \frac{Q}{\sqrt{\pi K \rho c t}} e^{\frac{-z^2}{4\alpha t}} \tag{1}$$

where z is the depth below the heated surface, Q is the injected energy density, K is the thermal conductivity, ρ is the density, c is the specific heat and α=K/ρc is the thermal diffusivity, respectively, of the tooth. The analysis of Eq.(1) shows that the temperature curve is inversely proportional to the thermal effusivity $(K\rho c)^{1/2}$ (other authors prefer the concept of thermal inertia, Kρc). Less conductive materials reach higher surface temperatures for the same heating pulse.
If attention is focused on surface temperature (z=0) the decays follow the expression:

$$T(0,t) = \frac{Q}{\sqrt{\pi K \rho c t}} = \frac{Q}{\sqrt{\pi K \rho c}} \frac{1}{\sqrt{t}} \qquad (2)$$

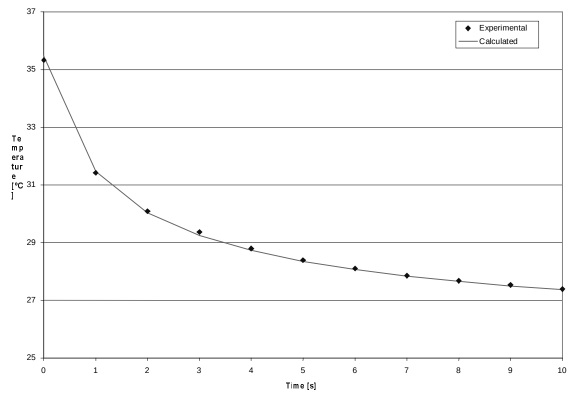


Figure 8 - Comparison between experimental and calculated temperature decay on tooth surface.

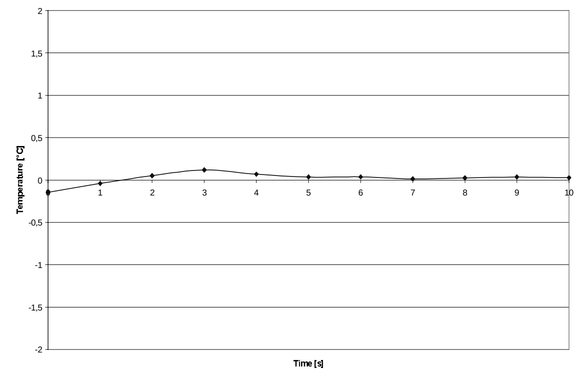
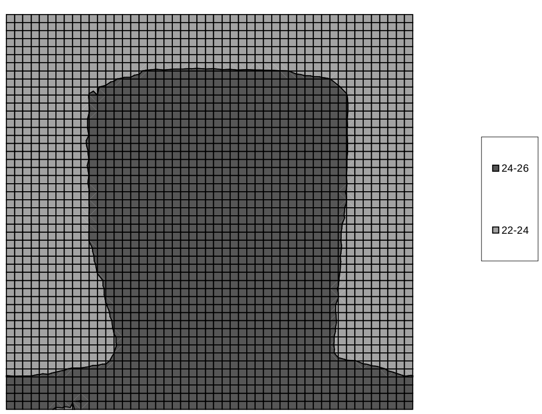


Figure 9 - Temperature differences between experimental and calculated thermal decay on tooth surface.



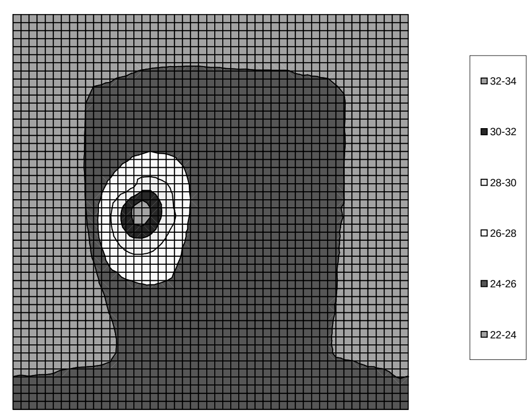


Figure 10 and 11 - Temperature map of the tooth surface before and after 2 s of laser pulses exposure (temperature in °C).

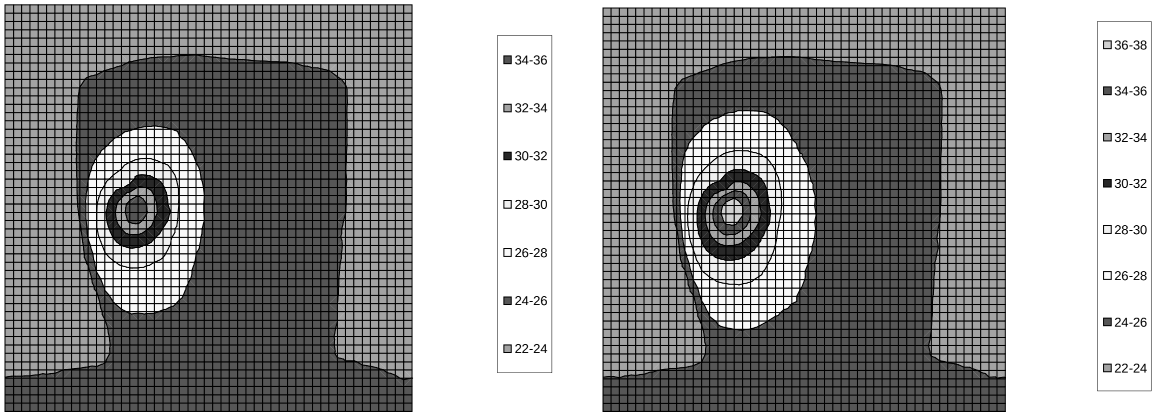


Figure 12 and 13 - Temperature map of the tooth surface after 4 s and 6 s of laser pulses exposure (temperature in °C).

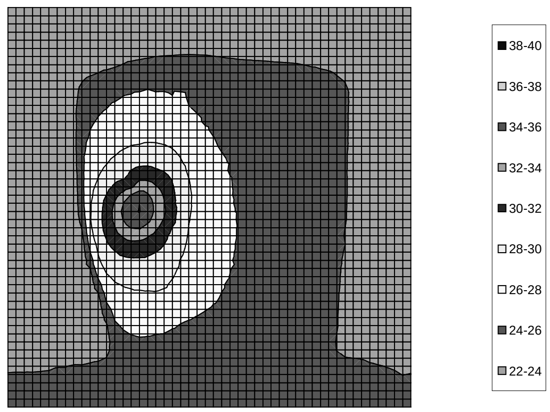


Figure 14 - Temperature map of the tooth surface after 8 s of laser pulses exposure (temperature in °C).

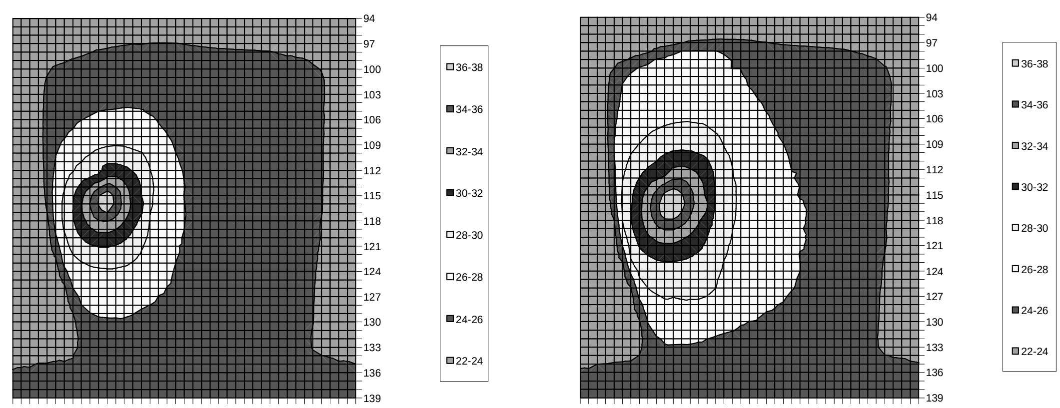


Figure 15 and 16 - Temperature map of the tooth surface after 10 s and 12 s of laser pulses exposure (temperature in °C).

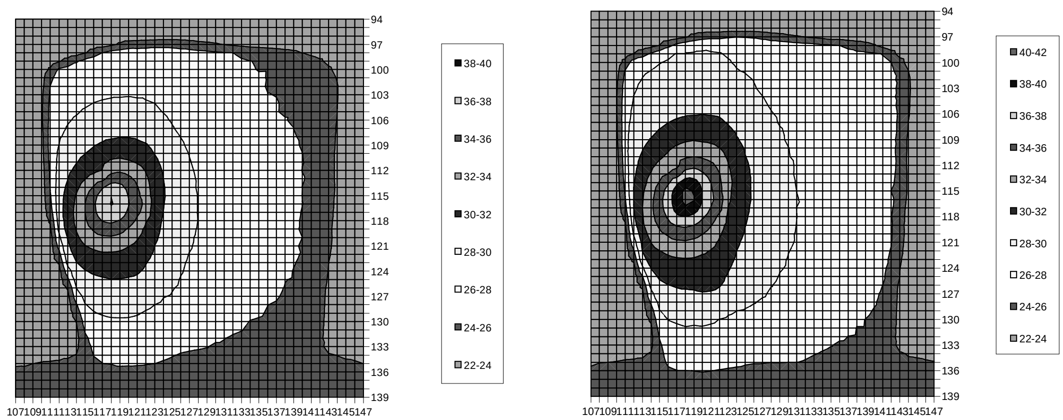


Figure 17 and 18 - Temperature map of the tooth surface after 18 s and 24 s of laser pulses exposure (temperature in °C).

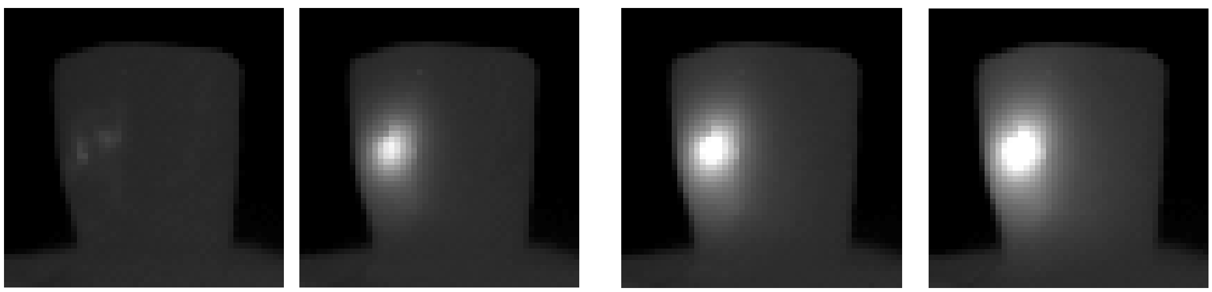


Figure 19 - Thermal images from the infrared camera reported in grey scale, relative to the laser exposure, after 0.16 s, 1.6 s, 3.2 s and 4.8 s.

In Figure 8, the temperature decay experimentally measured on a time base of 10 s on a point of the tooth surface has been reported. In the same Figure the temperature curve calculated using Eq.(2) has been reported. Results obtained have been corrected summing the room temperature during tests (24.7°C) to the calculated temperatures. It was estimated that using a value $Q/\sqrt{\pi K \rho c}$ =15.4 an excellent agreement can be found between theoretical model and experimental results (Figure 8). The differences obtained using experimental and calculated data are reported in Figure 9.

In Figures 10 to 18 the temperature map of the tooth surface during the laser pulses exposure is reported. The temperature maps of Figure 10–14 are composed by 49x49 measurement points on the tooth surface. Figure 10 reports the temperature map of the tooth surface before the first pulse. Temperature of the tooth surface ranges between 24 and 26 °C. Figures 11 to 14 report the temperature on the tooth surface at 2, 4, 6 and 8 s respectively. The maximum temperature has been measured on point (118,116) at 8 s and it is of 37.1 °C. It is also possible to note how after 8 s almost half of the tooth surface has increased, in average, the temperature of 2°C.
As example, the thermal images from the infrared camera are reported in grey scale in Figures 19 - 22. They are relevant to the heating transient, respectively after 0.16 s, 1.6 s, 3.2 s and 4.8 s of laser exposure. From the processing of these images the temperature map previously shown was obtained.
Figures 15 – 18, show the temperature maps measured on the tooth exposed to laser pulses for 24 s. The time steps selected among the Figures is of 6 s. The maximum temperature was reached after 24 s, on point (118,116) and it was of 40.5°C.

5. CONCLUDING REMARKS.

The use of Nd:YAG lasers in dentistry is attractive for tasks such as cavity preparation, bacterial reduction and root canal cleaning. In fact, they can reduce the pain of patients and therefore the need of anaesthesia. Studies have been conducted in order to select the best laser source for each dentist application, such as removal of dentine and enamel or removal of caries and stains. Contra-indications in use of lasers must be investigated. For example care must be taken in order to avoid the overheating of the pulp caused by the laser pulse penetration.

Nd:YAG laser pulses are becoming of interest also for the use in non contact, optical diagnostic procedures[12–16] for dentistry. In this procedures laser pulses are used to induce local bending moment, with consequent mechanical vibrations. The measurement of these vibrations is performed using LDVi techniques. LDVi results are employed for diagnostic purposes evaluating the modifications of the frequency behaviour of the tooth induced by the presence of teeth defects[15].

Authors have conducted tests in order to measure the temperature behaviour of the human tooth surface when it is exposed under Nd:YAG pulsed laser radiation of 532 nm of wavelength, 50 mJ of energy, 12 ns of pulse duration and 10 Hz of repetition frequency.

The measurement chain is based on a IR camera with 256x256 CCD sensor. Taking into account the noise in the sensor and the uncertainty of the calibration performed on the curve surface of the tooth, an accuracy of about 1 °C can be estimated.

Experimental data have been used to evaluate the value of the ratio $Q/\sqrt{\pi K \rho c}$, using a mathematical model[23]. This ratio gives important information about the tooth surface material properties. Thermal conductivity, density and specific heat can be estimated calculating the energy density of the laser exposure.

Data collected confirm the necessity to limit exposure of the tooth surface to laser pulses radiation. Maximum exposure time will depend mainly on four parameters: laser sources (in terms of the wavelength selected), power level, time duration and repetition rate of laser pulses. Using a Nd:YAG pulsed laser source, with a time duration of 12 ns, a power level of 50 mJ and a repetition frequency of 10 Hz, it is necessary to avoid exposure longer then 20 s in order to have a maximum temperature on the incidence point not higher then 40 °C. Figure 16, shows also the effect of the thermal diffusion on the tooth surface. Medical evaluation of the thermal effect of laser pulses should be further investigated in co-operation with medical doctor and dentists.

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