Scanning of Ultra-Short Laser Pulses in Dental Applications

Martin STRASSL, Ariej YOUSIF, Ernst WINTNER

Photonics Institute, Vienna University of Technology, Gusshausstrasse 27/387, 1040 Vienna, Austria
E-mail: martin.strassl+e387@tuwien.ac.at

Ultra-short laser pulses (USLP) have the potential for materials processing with almost no collateral thermal or mechanical damage. Thus they are well suited for hard tissue preparation in dentistry. But since sharp focusing has to be applied to reach the high intensities required for plasma-mediated ablation, the small focal spot has to be scanned over a larger area representing the cross section of a usual dental drill. This paper investigates cavity shape and morphology for two different pulse lengths, as longer pulses would allow access to cheaper laser sources for later industrial development of a medical device. 700 fs and 12 ps laser pulses were applied on plain human dentine slices with a pulse repetition rate of 35 kHz using a newly developed rotating scanner working in r/φ-coordinates. Cavity shape and morphology of different scanning patterns were evaluated using ESEM and 3D light microscopy.

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1. Introduction

Since the 1990ies, lasers are a well established tool for hard tissue preparation in dentistry [e.g. 1, 2]. In the commonly employed type of laser-assisted hard tissue preparation, usually tissue removal by water-mediated ablation is applied, usually being performed by erbium based laser systems. In spite of the high state of development of the actual devices, there are still some limiting factors present, such as the danger of inducing micro-cracks and heat accumulation at insufficient external cooling (the maximum allowed temperature rise in the dental pulp to preserve its vitality is about 5°C [3]). These deficiencies depend mainly on the ability of a suitable laser pulse for efficient evaporation of the embedded water in the tissue, governed by several factors like pulse duration, pulse shape and the intensity distribution (TEM profile) in the laser beam [4, 5].

To avoid these problems, already in the 1990ies a new approach was proposed by several authors, employing so-called ultra-short laser pulses having pulse durations in the picosecond and down to the femtosecond regime (e.g. [6, 7, 8]), thus allowing the application of plasma-mediated ablation. Beside the already well discussed medical requirements [6, 10, 11], the main demands for practical applicability are a sufficiently high ablation speed and the possibility of handling the laser device like a conventional dental drill.

Compared to conventional laser-assisted hard tissue ablation, a single ultra-short laser pulse removes just a very small volume of several hundred µm³ due to its usually small focal spot and low penetration depth [6]. The small focal diameter has to be applied in most cases to achieve the high energy densities required for plasma generation. Thus, a very high pulse repetition rate has to be applied to yield ablation speeds of several mm³ per minute, hence being comparable to water-mediated ablation. But just within the last three to four years, laser systems providing adequate pulse energies with a sufficiently high pulse repetition rate larger than 15 kHz became available, opening the way to high-speed ablation investigations.

To be able to handle the small focal spot together with the high pulse repetition rates also practically, lateral scanning of the single laser pulses has to be employed. This means the application of a defined movement of the laser beam over a certain area, placing one pulse beside the other. It allows on the one hand avoiding accumulation and incubation effects of the applied energy in the remaining material and on the other hand it yields better ablation results in terms of geometrical and morphological quality [6, 7].

Considering the fact of dentists being used to drilling tools with rotational symmetry yielding low stress concentration at rounded cavity edges, it was decided to apply a circularly shaped scanning pattern provided by a newly developed r/φ-scanner instead of using a conventional x/y-scanner with rectangular shaped scanning pattern. Furthermore, if the automatically scanned pattern (representing the conventional burr) is manually moved over the surface to be processed, only circular symmetric patterns will not result in a change of the intensity distribution on the target if the scanned pattern is moved in any arbitrary direction over the treated surface (see Fig.1).

Another problem for the practical implementation of ultra-short pulse lasers into a broad medical application are the high prices for suitable laser sources. Here the employment of slightly longer pulses (i.e. pulses in the short picosecond regime) would allow the use of significantly cheaper laser sources than those for femtosecond pulses (even around 600-700 fs). So the aim of this study was to investigate the ablation characteristics of different scanning algorithms with rotational symmetry and to evaluate the resulting macro- and microscopic quality of the generated cavities for pulse lengths in the femtosecond and short picosecond regime.

2. Materials and Methods

Prior to the experiments simulations of the intensity distribution generated by different scanning patterns were performed in Matlab. The results were compared to the real intensity distributions recorded by a CCD camera (Ophir Beam Star FX).

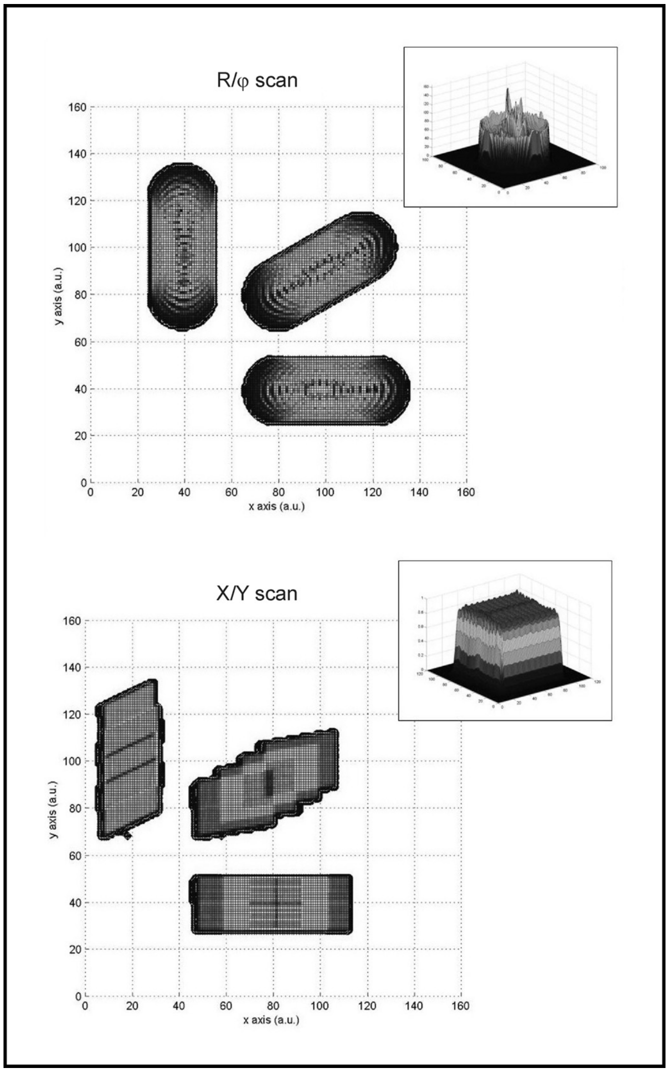

Fig. 1: Simulated resulting intensity distribution of a pattern with rotational symmetry (above) and a rectangular x/y-scanned pattern (below, line by line scan), both shifted in three different directions. The inserts at the upper right corner of each viewgraph depicted the static pattern of each algorithm. If the rectangular pattern is moved in any direction, the resulting intensity pattern on the irradiated surface depends on the angle between the geometrical principal axis and the direction of motion. The intensity distribution of the pattern with rotational symmetry is independent of the direction of motion. Both simulations were performed with constant motion velocity.

As stated above, for the experiments it was decided not to use a commercial x/y-scanner being best for the creation of rectangular shaped patterns, but to employ a device scanning in r/φ coordinates. Thus, circularly shaped patterns easily can be achieved. In the used r/φ-scanner (prototype developed by LINOS Photonics, Munich), a conventional galvo-mirror deflecting the beam in radial direction and a fast picture rotating prism adding the φ-coordinate were implemented. By applying different motion functions and frequencies to the inclined mirror and specific rotation frequencies to the prism, various scanning patterns could be generated.

For the ablation experiments in dentine, two laser sources with different pulse widths (700 fs and 12 ps) were applied:

The 700 fs laser source was a Yb:KYW system operating at 1030 nm with high pulse energies (≥100 µJ) at high pulse repetition rates (30-45 kHz) developed by IFSW, Stuttgart University [12, 13]. Thus, an average output power of 3.0 to 4.5 W can be achieved with this system.

The 12 ps laser source was a commercially available Nd:YVO4 laser operating at 1064 nm with pulse repetition rates of 100 kHz at pulse energies of 100µJ. (picoREGEN^{TM}, IC-10000 REG AMP Microprocessing, High Q Laser Production GmbH).

For the reported experiments both lasers were operated at a pulse energy of 100µJ and a pulse repetition rate of 35 kHz, yielding an average power of 3.5W.

To achieve comparability of the ablation results, all of the processed specimen should have the same material properties. However, as the specimens are concerning biological materials from different donators, each tooth has slightly different properties. To minimize the dispersion originating therefrom, only sound material was used being harvested from human third molars that had to be extracted only due to orthodontic reasons and not for conservative or restorative requirements. Second, it was tried to perform as many experiments as possible on the same tooth. Thus, to use the largest possible area, the experiments were performed only in dentine and not in enamel, as out of an adult tooth usually one dentine slice and one tooth stump can be obtained, resulting in a total surface area fitting for about 8 - 12 cavities of 2mm diameter resembling a larger dental bur. The rather large size of the cavities was chosen to have no difficulties in ESEM or 3D light microscope investigation due to a too high aspect ratio of the hole. Working in enamel would not allow this, as either a much smaller cavity diameter would have had to be selected or an ablation step would occur inside the cavity due to a material change over the processed area (compare e.g. [10], Fig. 3-70), thus interfering negatively with the evaluation of the homogeneity of the cavity shape.

Hence, ten freshly extracted, sound human third molars were chosen as samples for the ablation investigations. The occlusal enamel was removed using a diamond coated cutting-off wheel to obtain a flat dentine surface. The teeth were disinfected in an alcohol water solution (10% pure alcohol (96%), 90% H_2O) to prevent bacterial growth and stored in normal water until usage. Right before the ablation, teeth were taken out of the water, wiped clean and dried at

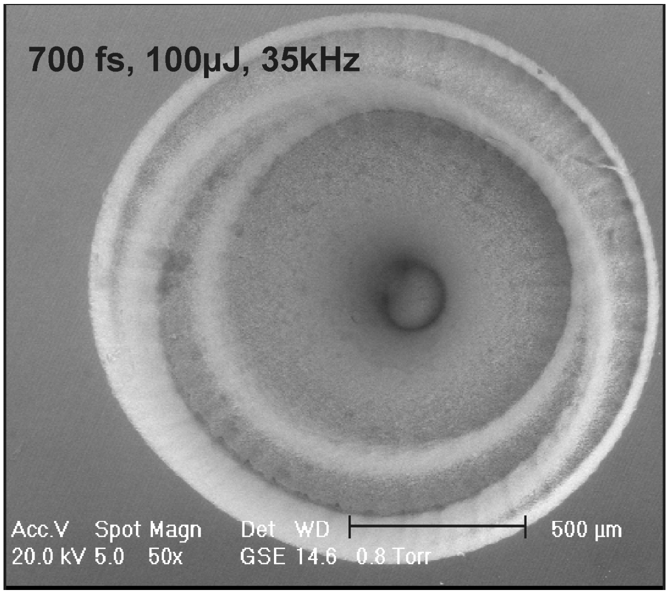

Fig. 2 Circularly shaped cavity in dentine prepared by ultra-short pulses (for set parameters see text). This cavity has an approximate diameter of 1.5 mm. Remarkable are the complete absence of micro-cracks and the very smooth and geometrically well-defined surfaces. The riffles on the prepared surfaces are caused by interference phenomena of the scanned pattern. No molten and re-solidified areas can be identified in this picture.

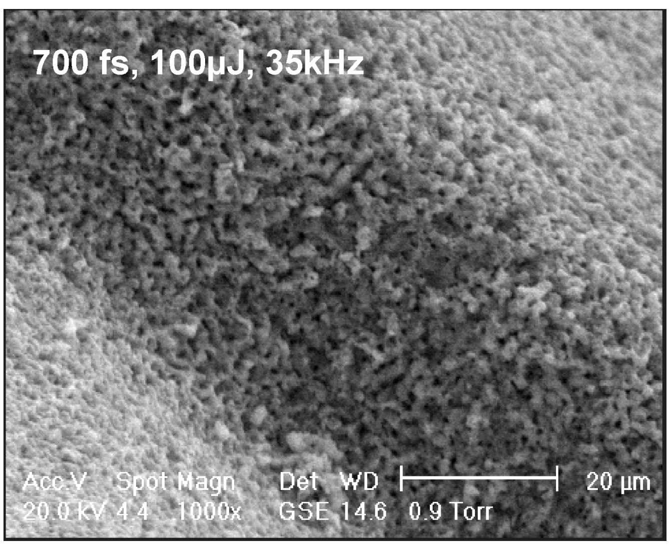

Fig. 3 Detail of the prepared dentine surface. The dark holes visible are opened dentine tubules. The micro-morphology of the surface shows a very fine micro-retentive pattern.

normal atmospheric conditions for 5 min. No compressed air or hot air fan was used to avoid excessive dehydration. After cavity preparation, the teeth were investigated under the light microscope and stored in water again until SEM investigation.

After the experiments, the topography of the created cavities was recorded by a digital light microscope with implemented 3D reconstruction software (Infinite Focus, Alicona Imaging, Grambach, Austria) and compared to the recorded intensity distribution.

3. Results

The prepared cavities show a very high micro- and macroscopic quality (Figs. 2, 3, 5). Remarkable are the very sharp rims and the very smooth and geometrically well-defined surfaces (Figs. 2 and 5). At higher magnification (Figs. 3 and 5), a very fine micro-retentive pattern (Fig.3) can be seen. Between the grain shaped microstructures, opened dentinal tubules are clearly visible. Opposite to the typical erbium laser treated surfaces, no “chimney structures”, i.e. less ablated, hypermineralized cirumtubular dentine formations are visible. Furthermore, not even smallest micro-cracks are visible under all magnifications, usually not being the case for cavities ablated by water mediation [10]. The depicted scanning electron micrographs show no signs of molten or re-solidified areas, thus indicating no significant overheating of the residual tissue, even under completely absence of artificial cooling.
If the sharp cavity rims depicted in figure 2 are investigated under higher magnification, they show a slightly irregular shape (Fig. 5, a and c). Like the riffled structures on the prepared surfaces in figure 2, they are mostly caused by interference phenomena in the scanning pattern. This occursdue to interference phenomena between the frequencies of the rotating prism and the oscillating the galvo-mirror (see below).

The stair-like structures with two half-moon shaped steps merging into each other along the side walls of the cavities occurred due to an alignment error in the internal setup of the rotating prism that appeared during its manufacturing. Hence, this error could not be eliminated with the present experimental setup.

Considering the relative ablation efficiency of the single pulses in the scanning pattern, a significant decrease of the ablated volume can be found in the regions with high pulse accumulations (compare Fig.4b: intensity distribution recorded on a CCD chip and Fig.4c: topography of a processed cavity reconstructed out of 3D light microscopy). This reduction is in good accordance to the decrease of ablation efficiency for high pulse overlaps or pulse accumulations reported in the literature [8, 7].

4. Discussion

The cavities processed with scanned subpico- and picosecond pulses show some highly advantageous characteristics for subsequent dental restoration. First, there are the very sharp cavity rims being indispensable for satisfying sealing of any filling material to prevent later secondary caries formation. Second, there are the smooth and geometrically well-defined cavity walls avoiding stress concentration under the load of chewing pressure, etc. The complete absence of a smear layer, the low thermal impact and the very low ablated volume per pulse allow the formation of a surface structure that could not be achieved with other preparation methods in just one preparation step: The very fine micro-retentive pattern of the cavity walls and bottom (Fig. 2 and 3) seems to be very helpful for providing good bond strengths between tissue and filling materials.

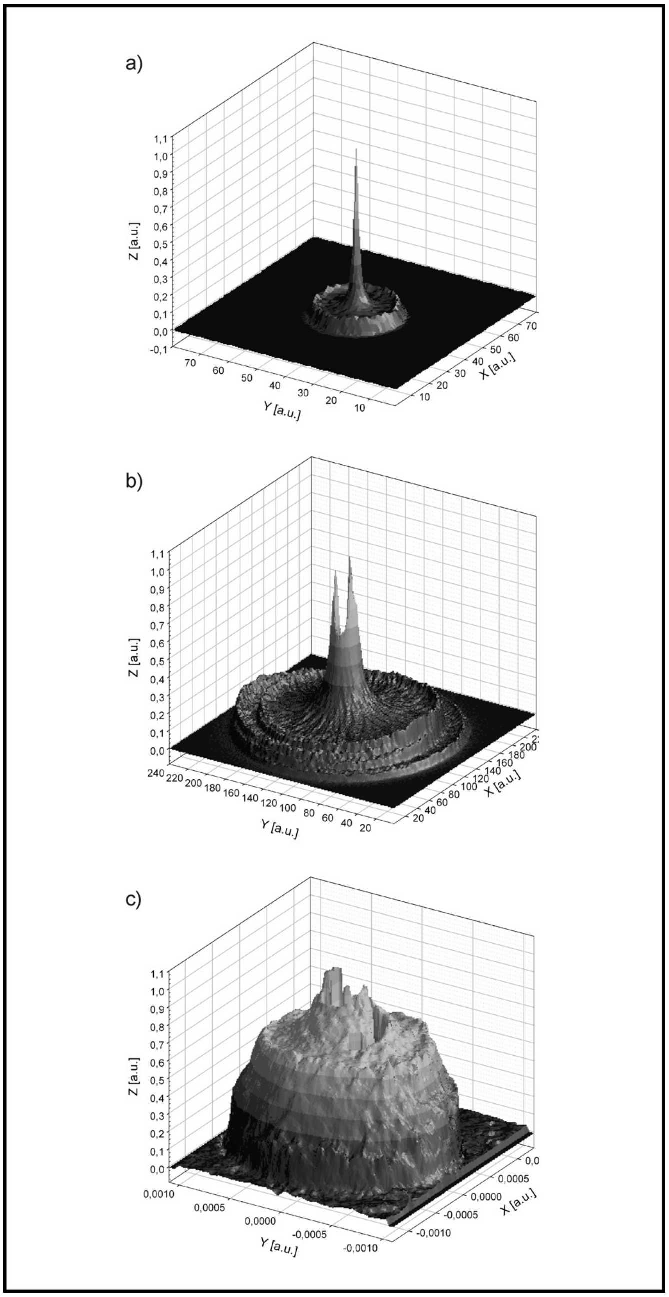

Fig. 4 Intensity distribution in the scanning pattern and resulting cavity shape:
a) Computer simulation (Matlab) of the intensity distribution. Except for the significant center peak, the energy distribution shows an almost cylindrical shape.
b) The center peak of (a) can be smeared out by changing the alignment of optical components in the beam path of the real setup.
c) Three dimensional digital micrograph reconstruction of the volume ablated by the algorithm shown in (b). Clearly lower peaks can be seen that are due to a loss of efficiency caused by the high pulse overlap leading to a superproportional temperature rise.

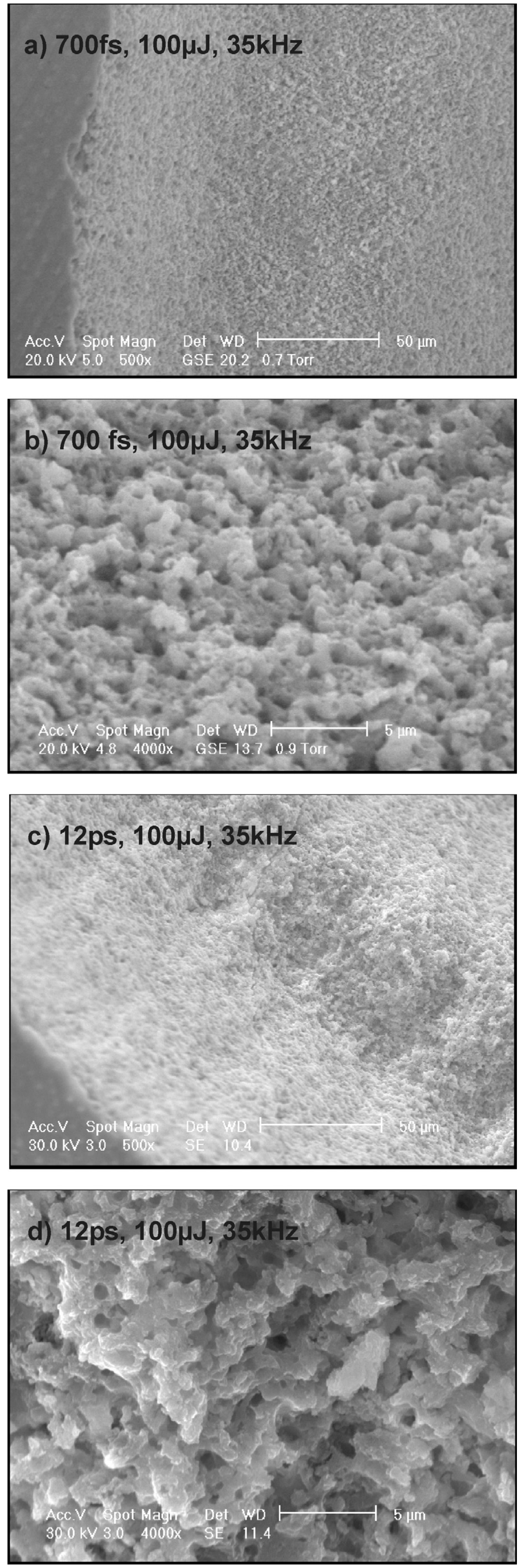

Fig. 5 (right) Comparison of the surface quality achieved with different pulse durations.
(a), (c): quality of the achieved cavity rim (ESEM, 500x)
(b), (d): detail of the surface morphology (ESEM, 4000x)

They get further improved by the opened dentinal tubules, allowing the formation of resin tags reaching from the filling material into the dentine. It is very remarkable that these effects are achieved without secondary treatment, e.g. acid etching. These results give rise to the assumption that potentially the etching technique could be avoided completely for routine application. However, this will have to be proved in further studies.

The irregularities in the surfaces and at the cavity rims under higher magnification are mainly a result of interference phenomena in the scanning pattern. As the patterns are generated by deflection of the pulses out of the initial beam path, the pulses are set along a certain pathway on the material surface. The temporal evolution of the geometrical shape of these ways together with the individual locations of the single pulses can lead to interference patterns, i.e. slightly more or less frequently hit areas, thus resulting in a slightly wavy shaped structure of the processed surfaces.

However, as the presented cavities were processed with fixed samples, the surface smoothness of cavities prepared with relative motion of the scanning patterns along the samples may differ from the reported results.

Besides the very gentle ablation mechanism, an additional advantage for the practical application of a scanned, sharply focused laser beam may be seen in the variable diameter of the scanning pattern. It can be readjusted very easily, particularly down to diameters that are usually very difficult to handle with conventional rotating instruments. By this, a door could be opened to not only minimal invasive, but rather maximum conservative dentistry [10], i.e. the preparation of carious lesions already at a very early state, thus helping to conserve a large amount of healthy tissue, being of particularly high importance in pediatric dentistry for a longtime preservation of the native teeth.

The absence of micro-cracks and molten areas on the processed cavity surfaces prove the low thermal impact of this preparation technology and clearly indicate the superiority of the application low energy pulses at a high pulse repetition rate to the commonly used high energy pulses at low repetition rates. The parameter settings for both techniques result in a similar average power (the applied 3.5 W are the same like the conventional power settings of an Erbium laser for dentine treatment). Moreover, as known out of many previous studies, the conventionally operated laser systems can already induce large molten areas and deep micro-cracks at this power setting [e.g. 10].

Taking a comparative look on the results for 700 fs and 12 ps pulse duration (Fig. 5), no significant difference can be found in morphology and microstructure of the processed surfaces. This is a very important finding, as the 12 ps pulses usually induce higher temperatures in the residual tissue than the 700 fs pulses, as they give more time to the free electrons to penetrate out of the plasma into the surrounding matrix. The reason for not yielding such a high difference in the heat influence of the resulting structures as it could have been expected seems to be that the well-known theoretical threshold of 1 ps for photon-phonon coupling [14] does not represent an incontrovertible borderline between no heat induction and heat induction, particularly as its theory bases on the assumption of several average values. Thus, also for pulse durations of approximately 0.7 ps already noteworthy heat induction will have to be taken into account, consequently decreasing the difference between the amount of induced heat between slightly below 1 ps and 12 ps. Nevertheless the pulse duration of 1 ps sometimes was considered as a strict demarcation line, thus authorizing just the application of shorter pulses to achieve the aimed results.

Considering the overall temperature induction, the reduction of ablation efficiency for large pulse accumulations [8] seems to play an important role besides pulse duration. As a decrease of ablation efficiency always stands for the increase of energy losses in the material, the residual heat will be increased automatically in such cases. Hence, as some scanning algorithms show areas of high pulse accumulations that clearly yield underproportional ablation depths in the processed cavities (compare e.g. figure 4, b and c), for them an additional induction of higher temperatures in the tissue can be assumed.

5. Conclusion and Outlook

Together with a suitable scanning algorithm, ultra-short laser pulses can be applied very successfully for cavity preparation in dental hard tissues. The evident gentle interaction of the pulses with the tissue bears the potential of a real minimal invasive preparation technology even at very small carious lesions. For the applied scanning pattern, a shape with rotational symmetry seems to be best suited, as only in this case independence of the resulting spatial energy distribution from the moving direction can be achieved.

Consequently, the temperature increase in the residual tissue will not only depend on the pulse duration, but also, and maybe even stronger, on the applied scanning procedure.

Comparing the pulse durations of 700 fs and 12 ps, the morphological results of the created cavities show a similar quality of the processed surfaces with opened dentinal tubules and micro-retentive structures being well suited for restoration with modern composites.

The use of short ps pulses would allow the implementation of cheaper laser systems for a broad field application in dentistry. Nevertheless, longer pulses always will yield a slightly larger temperature induction in the tissue. Considering that the critical temperatures for a vital tooth are too low to be indicated by micro-morphological changes in the tissue structure of dentine (about 5°C above body temperature, see above), additional accurate temperature measurements will have to be performed to verify if the longer pulses still can be applied absolutely safe without auxiliary cooling. This work is already in progress.

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References

[1] A. Mehl, L. Kremers, K. Salzmann, R. Hickel: Dent. Mater., 13, (1997) 246-251

[2] R. Hibst: "Technik, Wirkungsweise und medizinische Anwendung von Holmium- und Erbium-Lasern" (Ecomed, Landsberg, 1996)

[3] L. Zack, G. Cohen: OS,OM&OP, 19(4), (1965) 515-530

[4] M. Strassl, B. Üblacker, A. Bäcker, F. Beer, A. Moritz, E. Wintner: JOLA, 4(4), (2004) 263-270

[5] J. Meister, C. Apel, R. Franzen, N. Gutknecht: Lasers Med. Sci., 18, (2003) 112-118

[6] A.M. Rubenchik, L.B. Da Silva, M.D. Feit, S. Lane, R. London, M.D. Perry, B.C. Stuart, J. Neev: SPIE, 2672, (1996) 222-230

[7] M. Niemz: "Laser-Tissue-Interactions: Fundamentals and Applications" (Springer, Berlin, 1998)

[8] B.M. Kim, M.D. Feit, A.M. Rubenchik, E.J. Joslin, P.M. Celliers, J. Eichler, L.B. Da Silva: J. Biomed. Opt., 6(3), (2001) 332-338

[9] M. Strassl, A. Kasenbacher, E. Wintner: JOLA, 2(4), (2002), 213-222

[10] A. Moritz et al.: „Oral Laser Application" (Quintessenz, New York, 2005)

[11] J. Serbin, T. Bauer, C. Fallnich, A. Kasenbacher, W.H. Arnold: Appl. Surf. Sci., 197-198 , (2002)737-740

[12] A. Beyertt, D. Müller, D. Nickel, A. Giesen: OSA Trends in Optics and Photonics, 83, (2003) 407 (Optical Society of America,Washington DC, 2003)

[13] M.H. Niemz, A. Kasenbacher, M. Straßl, A. Bäcker, A. Beyertt, D. Nickel, A. Giesen: Appl. Phys. B, 79(3), (2004) 269-271

[14] M.D. Feit, A.M. Rubenchik, B.W. Shore: SPIE, 2672, (1996) 243-249

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