Scanning of Ultra-Short Laser Pulses in Dental Applications. A Comparison of Scanning Algorithms and Pulse Durations

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Purpose: 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 must be scanned over a larger area representing the cross section of a conventional dental drill. This paper investigates cavity shape and morphology for two different pulse lengths, as longer pulses would allow less expensive laser sources to be used in later industrial development of a medical device.

Materials and Methods: 700 fs and 12 ps laser pulses were applied on human dentin 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.

Results: Ablated surfaces show a high macro- and microscopic quality. The achieved microretentive patterns show promise of providing good bonding to composite resin filling materials.

Conclusion: Even at high pulse repetition rates, laser pulses in the low picosecond regime are very well suited for hard tissue ablation. The absence of collateral damage makes them as applicable for dental hard tissue preparation as femtosecond pulses.

Keywords: scanning, ultra-short laser pulses, cavity preparation, conservative dentistry, tissue processing, preparation quality.

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Since the 1990s, the laser in general is a well established tool for hard tissue preparation in dentistry.[1,2] Conventional laser-assisted hard tissue preparation usually effects tissue removal by water-mediated ablation, and is commonly performed by erbium-based laser systems. In spite of the high state of development of the current devices, some limiting factors still exist, such as the danger of inducing microcracks and heat accumulation in case of insufficient external cooling (to maintain vitality, the maximum allowable temperature rise in the dental pulp is about 5°C[3]). These deficiencies are chiefly related to the ability of a given laser pulse to efficiently evaporate the water embedded in the tissue, and are governed by several factors, such as pulse duration, pulse shape and the intensity distribution (TEM profile) in the laser beam.[4,5]

To avoid these problems, a new approach was proposed already in the early 90s by several authors employing so-called ultra-short laser pulses having pulse durations in the picosecond and down to the femtosecond regime.[6-8] Besides the already well-discussed medical requirements,[6,10,11] the main demands for practical applicability are a sufficiently high ablation speed and

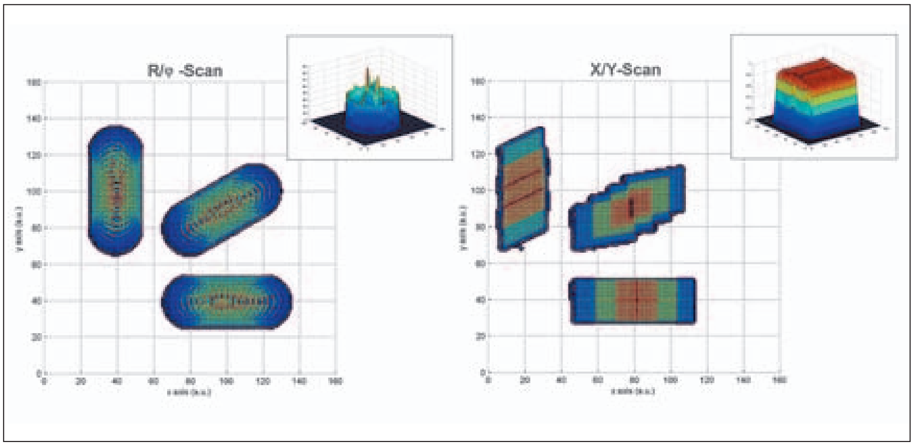

Fig 1 Simulated resulting intensity distribution of a pattern with rotational symmetry (left) and a rectangular x/y-scanned pattern (right, line by line scan), both shifted in three different directions. The static pattern of each algorithm is depicted in the inserts at the upper right corner of each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

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 μm^3 due to its small focal spot and low penetration depth.[6] Thus, a very high pulse repetition rate must be applied to reach ablation rates of several mm^3 per minute, therefore being comparable to water-mediated ablation. 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 have become available, thus making high-speed ablation studies possible.

Combined with the high pulse repetition rates, lateral scanning of the single laser pulses must be employed. This means the application of a defined movement of the laser beam over a certain area, placing one pulse beside the other. Thus, the treatment of an area larger than just the focal spot becomes possible. On the one hand, this allows avoiding accumulation and incubation effects of the applied energy, and on the other hand, it yields better ablation results in terms of geometrical and morphological quality.[6,7]

Considering the fact that dentists are accustomed to rotating instruments with rotational symmetry and low stress concentration at rounded cavity edges, the authors decided to apply a circular scanning pattern, provided by a newly developed r/φ scanner, instead of using a conventional x/y scanner. Furthermore, if the automatically scanned pattern (representing the conventional bur) is manually moved over the surface to be processed, only circularly symmetrical patterns will not result in a change of the intensity distribution on the target, if the scanned pattern is not moved along one of its geometrical principal axes over the treated surface (see Fig 1).

Thus, 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 cavities generated.

MATERIALS AND METHODS

Prior to the experiments, we performed simulations of the intensity distribution of different scanning patterns using the mathematical modelling software Matlab (The MathWorks; Natick, MA, USA). The results were compared to the real intensity distributions recorded by a CCD camera (Ophir Beam Star FX, Ophir Optronics; Jerusalem, Israel).

For the experiments, we decided not to use a commercial x/y scanner (which would be best for the creation of rectangular patterns), but to employ a device scanning along r/φ coordinates. Thus, circular patterns can easily be achieved. In the r/φ scanner used (prototype developed by LINOS Photonics; Munich, Germany), a conventional galvo-mirror deflecting the beam in a radial direction and a fast picture rotating prism adding the φ-coordinate are implemented. By applying different motion functions and frequencies to the inclined mirror and specific rotation frequencies to the prism, various scanning patterns can be generated.

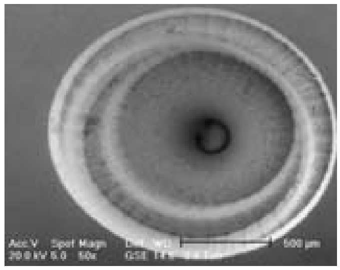

Fig 2 Circular cavity in dentin prepared by ultra-short pulses (for set parameters see text). This cavity has an approximate diameter of 1.5 mm. The complete absence of microcracks and the very smooth and geometrically well-defined surfaces are remarkable. The riffles on the prepared surfaces are caused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

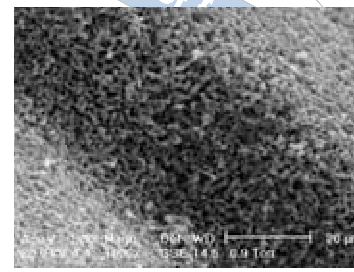

Fig 3 Detail of the prepared dentin surface. The dark holes visible are opened dentin tubules. The micromorphology of the surface shows a very fine microretentive pattern.

For the ablation experiments in dentin, laser sources with two 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 to 45 kHz) developed by the IFSW (Institut für Strahlwerkzeuge) Stuttgart University.[12,13] Thus, an average output power of 3.5 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. (picoREGENTM, IC-10000 REG AMP Microprocessing, High Q Laser; Hohenems, Austria). The pulse energy was set to 100 µJ.

For the ablation experiments, 10 freshly extracted human third molars were used. The occlusal enamel was removed using a diamond coated cutting wheel to obtain a flat dentin 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 ablation, the teeth were taken out of the water, wiped clean, and dried at normal atmospheric conditions for 5 min. Neither compressed air nor a hot-air fan were used, to avoid excessive dehydration. After cavity preparation, the teeth were investigated under the light microscope and stored in water again until SEM examination.

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.

RESULTS

The prepared cavities show a very high micro- and macroscopic quality (Figs 2, 3, 5). The very sharp rims and the very smooth and geometrically well-defined surface (Figs 2 and 5) are remarkable. At higher magnification (Figs 3 and 5), a very fine microretentive pattern (Fig 3) can be seen. Between the grain-shaped microstructures, opened dentinal tubules are clearly visible. As opposed to the typical erbium-laser treated surfaces, no "chimney structures", ie, fewer ablated, hypermineralized cirumtubular dentin formations are visible. Furthermore, not even the smallest microcracks are visible under any magnification, which is usually not the case for water-mediated ablated cavities.[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 complete absence of artificial cooling.

The sharp cavity rims depicted in Fig 2 have a slightly irregular shape if viewed under higher magnification (Fig 5, a and b). Like the riffled structures on the prepared surfaces in Fig 2, they are caused by interference phenomena in the scanning pattern. These phenomena occur due to interferences between the rotation frequency of the rotating prism and the oscillation frequency of the galvo-mirror.

The stair-like structures in the side walls of the cavities occurred due to an alignment error in the rotating prism, consisting of several optical components fixed rigidly to each other. Hence, this error cannot be eliminated with the present experimental setup.

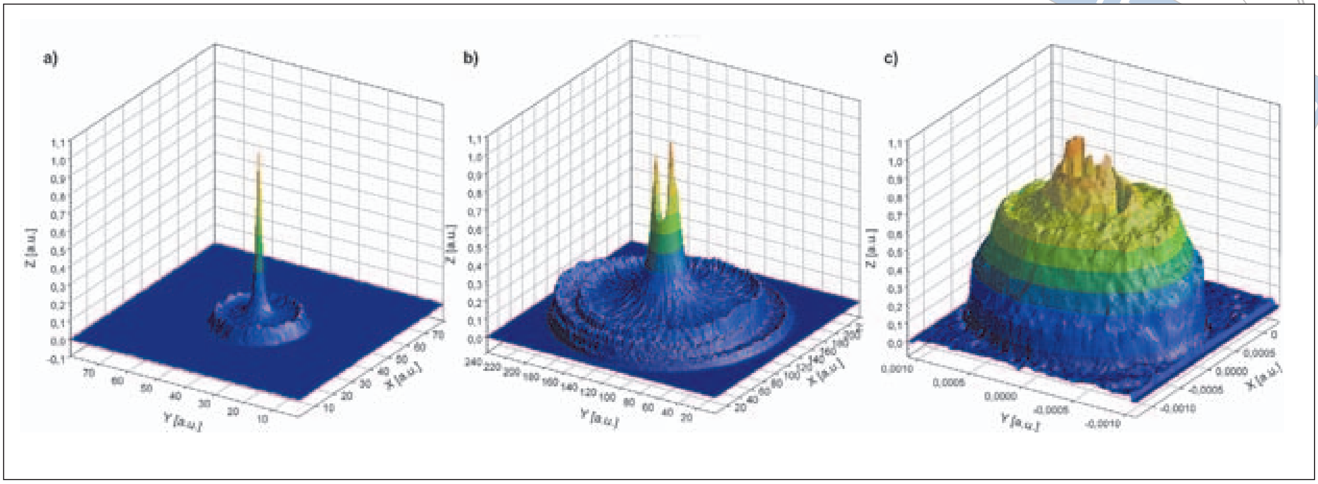

Fig 4 Intensity distribution in the scanning pattern and resulting cavity shape.

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 redistributed over a larger area 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). Noticeably 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.

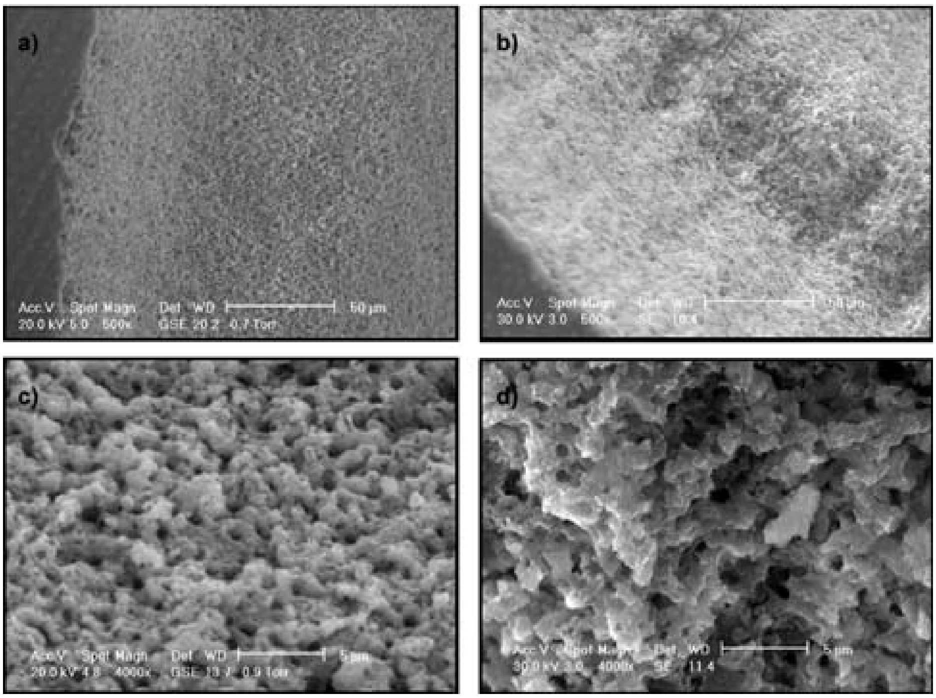

Fig 5 Comparison of the surface quality achieved with different pulse durations. Upper row: quality of the achieved cavity rim (ESEM, 500X): a) 700 fs pulses, b) 12 ps pulses. Lower row: detail of the surface morphology (ESEM, 4000X): c) 700 fs pulses, d) 12 ps pulses.

Comparing the processed topography of the cavities to the corresponding intensity profile recorded by the CCD camera (Fig 4, b and c), a significant reduction of the ablated volume in regions with high intensity can be found. This is in good accordance with the decrease of ablation efficiency for high pulse overlaps or pulse accumulations reported in the literature.[7,8]

DISCUSSION

The cavities presented show some advantageous characteristics for subsequent dental restoration. First, there are the very sharp cavity rims, which are indispensable for satisfactory sealing of any filling material. Second, there are the smooth and geometrically well-defined cavity walls, which avoid stress concentration under load. The complete absence of a smear layer, the low thermal impact, and the very low ablation per pulse allow the formation of a surface structure which is not achievable with other preparation methods: The very fine microretentive pattern of the cavity walls and bottom (Figs 2 and 3) seems to be very helpful for providing good bond strengths between tissue and filling materials. They are further improved by the opened dentinal tubules, allowing the formation of resin tags in the filling material. It is very noteworthy that these effects are achieved without secondary treatment, eg, acid etching. These results indicate that it may be possible to omit the etching technique completely for routine application. However, this will have to be proven in further studies.

The irregularities in the surfaces and at the cavity rims under higher magnification are 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 paths, together with the individual locations of the single pulses, can lead to interference patterns, ie, slightly more or less frequently hit areas, thus resulting in a slightly wavy 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. Thus, this may enable preparation of carious lesions at a very early state, therefore helping to conserve a large amount of healthy tissue. This is particularly important in pediatric dentistry for the long-term preservation of the natural teeth.

The absence of microcracks and molten areas prove the low thermal impact and the advantage of a high number of low energy pulses compared to the usual high energy pulses at low repetition rates. The common parameters in both cases result in a similar average power (the applied 3.5 W are comparable to conventional erbium laser settings for dentin treatment). As known from many previous studies, low-repetition laser systems can already induce large molten areas at these average power settings.[10]

Comparing the results for 700 fs (= 0.7 ps) and 12 ps pulse duration (Fig 5), no significant difference can be found in morphology and microstructure of the processed surfaces, although the 12 ps pulses are believed to induce higher temperatures than the 700 fs pulses. Certainly, the picosecond pulses will induce more heat than the femtosecond pulses, as they give more time to the free electrons to penetrate out of the plasma into the surrounding matrix; however, 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 is based on the assumption of several average values. Thus, even for pulse durations of approximately 0.7 ps, relevant heat induction will still have to be taken into account. Nevertheless, 1 ps was sometimes considered a strict demarcation line, thus authorizing only the application of shorter pulses to achieve the desired results.

The results presented here show that there seems to be no significantly higher temperature induction from 0.7 to 12 ps, as the structure of the cavities of both pulse durations is very similar.

Considering temperature induction, the reduction of ablation efficiency for large pulse accumulations[8] seems to play a highly important role, in addition to pulse duration. As a decrease of ablation efficiency always represents implies 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, for instance, Fig 4, b and c), for them an additional induction of higher temperatures in the tissue can be assumed.

Consequently, the temperature increase in the residual tissue depends not only on the pulse duration, but also and perhaps to an even greater extent, on the applied scanning procedure.

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 truly minimally invasive preparation technique, even for very small carious lesions. For the applied scanning pattern, a shape with rotational symmetry seems to be best suited, as only in this case can independence of the resulting spatial energy distribution from the direction of motion be achieved.

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 microretentive structures which are well suited for restoration with modern composites. The use of short ps pulses would allow the implementation of less expensive laser systems for a broad field of application in dentistry. Nevertheless, longer pulses will always yield a slightly larger temperature induction in the tissue. Considering that the critical temperatures for a vital tooth are too low to be reflected in micromorphological changes in the tissue structure of dentin (about 5°C above body temperature, see above), additional, accurate temperature measurements must be performed to verify whether the longer pulses can still be applied absolutely safely without auxiliary cooling. This work is already in progress.

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