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Tooth ablation using a CPA-free thin disk femtosecond laser system

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ABSTRACT Caries – the most frequent cause for dental surgery – still is mainly treated with conventional mechanical drills, although lasers have meanwhile been successfully applied to various clinical disciplines. Since ultrashort laser pulses with sufficient pulse energies have only been available at low repetition rates (< 1 kHz) in recent decades, solely continuous wave radiation or pulse durations longer than thermal diffusion processes were applied with the result of severe thermal damage and pain. In this report we present results on dental tissue ablation obtained with a novel thin disk Yb:KYW regenerative amplifier system that does not require chirped pulse amplification (CPA). We show that femtosecond laser pulses provide us with today's optimal tool to treat dental decay in an acceptable time, in an excellent quality, and with unsurpassed caries selectivity. The superior quality is a result of the non-thermal laser-tooth interaction. All our results are based on environmental scanning electron microscopy.

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1 Introduction

The first lasers to irradiate teeth were pulsed ruby lasers [1, 2]. However, due to their relatively long pulse durations of up to a few hundred microseconds, these lasers induced severe thermal side effects inside the tooth substance. Similar findings were reported just a few years later using a CO_2 laser [3]. Meanwhile, several experiments have been conducted using alternative laser systems, such as Er:YAG lasers [4–6], Ho:YAG lasers [7], excimer lasers [8, 9], and frequency-doubled Alexandrite lasers [10, 11]. All of these lasers still induce severe thermal effects or do not supply sufficient ablation rates (ablated volume per time) to compete with mechanical drills [7, 12, 13].

In 1993 M.H. Niemz first proposed the application of ultrashort laser pulses to overcome thermal side effects and insufficient ablation rates [7]. Using a picosecond Nd:YLF laser, ablation qualities superior compared to any other laser systems had been achieved [14–16]. Although, at the early stage of experiments, uncertainty predominated concerning potential shock wave effects, it has meanwhile been verified by independent tests that mechanical impacts are negligible [13]. Due to the recent progress in ultrashort laser technology, even femtosecond lasers have meanwhile been introduced to laser dentistry [17–19]. However, the general problem encountered when directly amplifying femtosecond laser pulses to sufficient energies is that non-linear distortions and optical damage may occur due to unacceptable high peak intensities. Usually chirped pulse amplification (CPA) is applied to amplify femtosecond laser pulses [20]. The disadvantages of these CPA systems are their high complexity and the requirement for a very precise alignment of the stretcher and compressor. Our thin disk regenerative amplifier concept uses large cross-sectional areas to avoid high peak intensities [21]. Thus it eliminates the need for CPA in the amplification of femtosecond pulses to the energy level needed for medical applications, giving promise for an affordable and pain-free laser dentistry in the near future.

2 Materials & methods

The regenerative amplifier system (Fig. 1) consists of a seed laser, a telescope, a beam separation unit, and an amplifier laser [21]. A diode-pumped Yb:glass laser oscillator (HighQ-Laser, Austria) is applied as the femtosecond seed source. A thin film polarizer in combination with a Faraday rotator and a half-wave plate are used to separate the amplified pulses from the seed pulses. The amplifier resonator is designed for TEM_{00} operation. Beam quality in pulsed mode is measured to be $M^2 = 1.2$. A BBO Pockels cell and a thin film polarizer are used for injection and ejection. The repetition rate of the system is limited by the Pockels cell driver (Behlke Electronic GmbH, Germany), which can be operated up to 45 kHz so far. Amplifying medium is a 100 µm thick and 10% doped Yb:KYW *b*-cut crystal mounted in a thin disk laser head [22]. The crystal is pumped by a 60 W fiber-coupled diode laser (Jenoptik GmbH, Germany) at a wavelength of 981 nm. Gires–Tournois interferometer (GTI) mirrors are implemented inside the resonator to compensate the pos-

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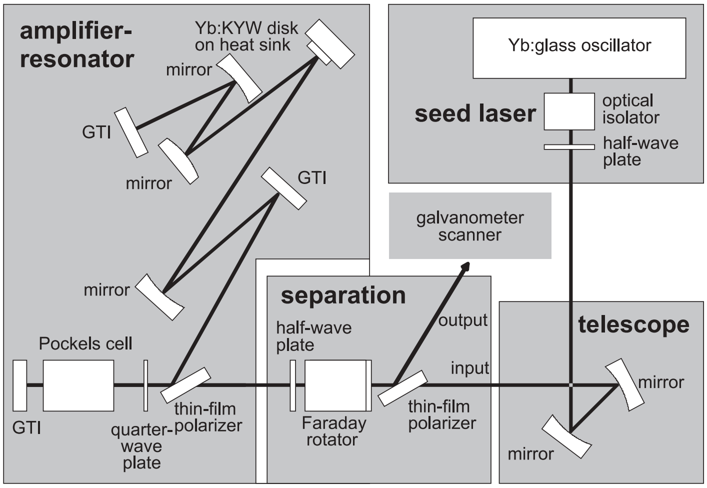

FIGURE 1 Schematic setup of the femtosecond laser system without CPA

itive group velocity dispersion of the resonator.

The amplifier provides laser radiation at a wavelength of 1030 nm with pulse energies up to 160 μJ and pulse durations below 900 fs. Cavities in teeth are ablated by scanning the focused laser pulses with a computer controlled galvanometer scanner (Linos, Germany) over the surface of the samples. The diameter of the focal spot is set to about 70 μm.

Extracted human third molars are used as samples in this study. The teeth are collected after the patients' informed consent is obtained. They are stored in pure water. Immediately before laser irradiation each tooth is dried with non-fuzzing tissue and left at surrounding conditions for 1 min to dry up completely. No pressure air is used to prevent excessive dehydration. All teeth are treated within one week following extraction. High magnification photographs of the processed samples are obtained by using an environmental scanning electron microscope (FEI/Philips XL30 ESEM, Netherlands). The acceleration voltage of the electron microscope is set to 20 kV. The pressure inside the ESEM is set to 0.9 Torr or 1.2 mbar, respectively.

3 Results

Environmental scanning electron microscopy demonstrates the ability of the femtosecond Yb:KYW amplifier system to produce extremely precise cavities in human teeth (Fig. 2). The cavity shown is located within healthy

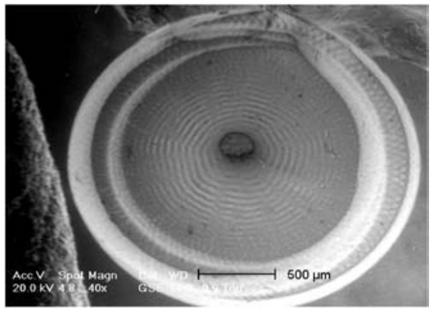

FIGURE 2 ESEM of a cavity prepared in healthy dentine

dentine. It has a diameter of 2.2 mm and a depth of approximately 500 μm. The roughness of the cavity bottom is of the order of 30 μm and thus facilitates the direct adhesion of most filling materials without any etching gel. The cavity wall (Fig. 3) is extremely steep and clean. The cavity itself is created by scanning a total number of about two million laser pulses within a disk shaped pattern. The pulse energy is set to 75 μJ corresponding to a pulse width of 650 fs. The focal spot size is about

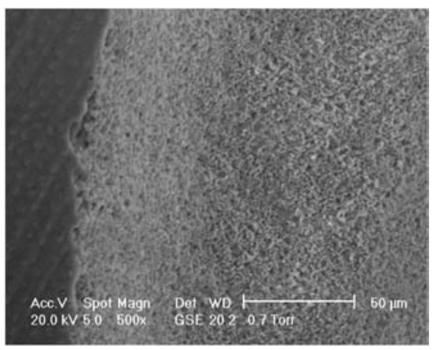

FIGURE 3 ESEM of a cavity wall prepared in healthy dentine

70 μm. At a repetition rate of 35 kHz the whole procedure takes about 1 minute only. Selected pulse energy and repetition rate yield a mean laser output power of 2.6 W. Carious lesions are ablated approximately ten times faster.

4 Discussion

When comparing femtosecond laser dentistry with all previous dental laser applications [1–11], the quality achievable with femtosecond laser pulses is very impressive. This quality is primarily due to the single fact that thermal side effects are eliminated completely when applying femtosecond laser pulses. The duration of a femtosecond laser pulse is so short that its interaction with the tooth does not allow heat to diffuse into the tooth [13]. The type of interaction is a pure plasma-induced ablation [13], i.e., the tooth is ablated by converting its components into a physical plasma. This mechanism comes with the important advantage of being very precise, since the plasma conversion is localized to the very focus of the laser beam.

Due to high pulse repetition rates of up to 45 kHz tooth ablation rates superior to Er,Cr:YSGG or Er:YAG lasers become available that are expected to meet conventional slow speed mechanical drills at 500–800 rpm.

The results described here prove that femtosecond laser pulses are a considerable alternative to the mechanical drill for the removal of dental decay or caries. For the first time ever, dentists now have an objective, reproducible, and minimally invasive concept for the treatment of carious lesions. Due to its caries selectivity, this novel technology eliminates any over-excavation and lowers the odds for an artificial pulp exposure. By reducing the ablation of sufficiently mineralized ''healthy'' tooth substance to a minimum, the need for expensive dental crowns and bridges is likely to significantly decrease in the future. Furthermore, the treatment is expected to be completely pain-free, because the femtosecond laser operates contactless and non-thermal.

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