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# High-Speed Laser Drilling for Dental Implantation: Ablation Process and Applicator Technology

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**Abstract:** Conventional mechanical drilling for implant placement is limited to specific geometry and orientation, resulting in incorrect positioning and inadequate anchoring in thin or porous bone. This study presents the development of a laser-based ablation process and an applicator technology for precise and fast laser drilling in the oral cavity. For the process development, a $CO_2$ laser with a wavelength of $10.6\,\mu m$ was used. Pulse durations between $10\,\mu s$ and $400\,\mu s$ were investigated for fast laser drilling with low thermal impact. For efficient ablation and cooling of the bone tissue, we applied a fine water spray. The laser applicator is designed with an integrated scanning module, focusing optics and a compact water spray system with three spray nozzles in the applicator tip. The geometry of the cavities was analyzed using digital microscopy and scanning electron microscopy, allowing to measure the ablated volume and depth as well as investigating the bone microstructure. This study demonstrates a laser ablation process capable to generate cavities with an ablation rate of $1.75\,mm^3/s$ which is about 80% higher than previously reported. At this ablation rate the melted zones were smaller than $30\,\mu m$. This paper demonstrates a concept for a dental laser drilling system with a fast ablation process and a highly-integrated applicator for treatment in the oral cavity.

**Keywords:** Dental Implantology, Implantation, Laser Ablation, Laser Drilling, Applicator, Handpiece, Laser Surgery, Digitalisation, Laser osteotomy

# 1 Introduction

Dental implantation has become safer, more aesthetic, and affordable due to advances in implant components and techniques. The entire workflow, from 3D planning software to the manufacturing of implants can now be digitized [1]. The implant post, abutment and prosthesis can be manufactured using automated or semi-automated processes. The implantation process involves drilling with a small diameter bit that is stepwise increased to prevent fractures. However, a whole drill set is necessary for each implant system, and there are more than 1300 different types of implants on the market [2]. A laser-based implantation system can drill an individual hole for every implant on the market, providing individualization in terms of diameter, length and conicity. Such system could integrate the implantation process in the digital workflow using imaging data to plan the bore hole. An optical monitoring and control system could be integrated, lowering the risk of irreversible damage to sensitive structures, such as the inferior alveolar nerve (IAN). This complication can occur in up to 40% [3–5] of all cases and cause numbness, pain, and taste loss [5].

## 1.1 Relevant work

Laser ablation of bone tissue with infrared laser sources is based on the process of thermo-mechanical ablation, that has already been documented in previous studies [6]. This ablation process has proven to be fast while preventing carbonization of the remaining bone tissue [7, 8]. $CO_2$ laser sources as well as Er:YAG laser sources are well-established for hard tissue ablation [7–9]. To drill a hole for one common implant a diameter of $3.8\,mm$ in a depth of up to $11\,mm$ is necessary. A common dental drill using two different drill bits needs $60\,s$ which results in an ablation rate of $2\,mm^3/s$. The highest ablation rate for laser drilling of bone tissue documented is $0.94\,mm^3/s$ using a Ho:YAG laser source generating pulses of $600\,\mu s$ duration [10]. With high repetition rates of $20\,kHz$ and a short pulse duration of $400\,ns$ an ablation rate of $6\,mm^3/s$ for non-thermal laser cutting was demonstrated [9]. Nevertheless, the maximum cutting depth was limited to $6\,mm$.

In the field of hard tissue ablation for dental applications, two established scanning handpiece systems are the Fotona Lightwalker AT dental laser with the X-Runner handpiece and the Convergent Dental Solea laser. Both handpieces utilize

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digital beam steering, mostly based on galvanometer scanners. Both laser systems incorporate a water spray system at the tool tip, with the former utilizing an Er:YAG laser and the latter employing a $CO_2$ laser with $9.3\,\mu m$ wavelength. These systems are only reported to perform surface treatments down to $2\,mm$ ablation depth. Concerning their application in implantology, the reports refer to soft tissue ablation in order to uncover as well as detoxify the implants and treating periimplantitis. However, there are no reports on these systems ever being used for drilling cavities for implantation.

# 2 Methods

The samples were prepared from fresh bovine cortical bone. For the experiments, a $CO_2$ laser source SCx10 from Rofin-Sinar with a wavelength of $\lambda = 10.6\,\mu m$ was used, generating pulses with pulse durations between $10\,\mu s$ and $400\,\mu s$. For the investigation of the ablation process, the $CO_2$ laser beam was focused and deflected on the surface of the bone sample, using the focus- and scanning system Axialscan-30 Digital II from RAYLASE. The beam was focused to a spot of $150\,\mu m$, resulting in a maximum fluence of $\Phi = 200\,J/cm^2$. For the ablation of a cylindrical structure, a spiral scanning pattern was used with a pitch of $0.1\,mm$ and a diameter of $3.8\,mm$. The pulse duration $t_P$ was investigated in a range between $20\,\mu s$ and $400\,\mu s$. For a constant duty cycle of $10\,\%$, the repetition rate $f_R$ according to the pulse duration was between $250\,Hz$ and $10\,kHz$, resulting in a mean power between $P = 18\,W$ (for $t_P = 10\,\mu s$) and $P = 29\,W$ (for $t_P = 100\,\mu s$). The scanning pattern, including the pulse overlap and the ablation duration were kept constant for reasons of comparability. The ablation process was continuously cooled with a water spray, that generates a water layer of a few micrometer thickness on the sample surface. The experimental setup is shown in Fig.1.

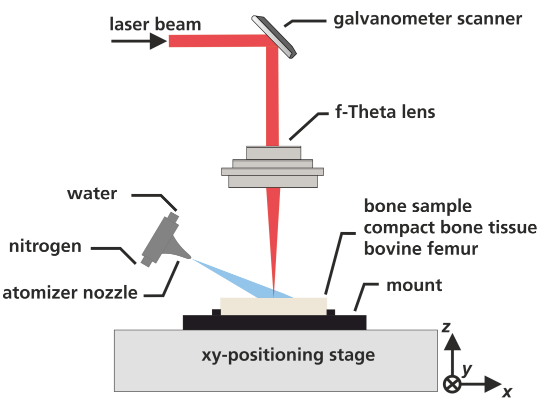


**Fig. 1:** Experimental setup for the investigation of hard tissue ablation with pulsed $CO_2$ laser radiation on bovine cortical bone

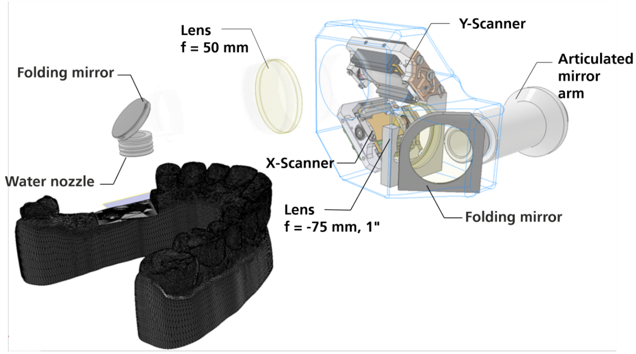


**Fig. 2:** CAD view of the handpiece showing the placement of the optics, planar galvanometer scanners and water spray nozzle within a compact housing.

## 2.1 Sample Analysis

For determining the ablation rate, the volume of the ablated bore hole is measured by 3D digital microscopy, using the microscope VHX6000 from Keyence with image stacking of $10\,\mu m$ depth resolution. From the knowledge of the scanning pattern and ablation cycles, the ablation duration can be calculated. To investigate the thermal and mechanical impact of different laser parameters on the bone microstucture, scanning electron microscopy (SEM) is used. The SEM was performed, using an Apreo 2 from Thermo Fisher Scientific. The laser processed bone samples are dried for about 30 minutes at a temperature of 120°C, and sputtered with gold by physical vapour deposition.

## 2.2 Applicator Development

Using optical simulation software (Zemax OpticStudio), an optical system was designed to meet the predefined requirements of focus diameter, depth of field, and scanning range. Next, the mechanical construction was developed with the aim to create a compact design for ergonomic handling and placement of the handpiece tip at any location on the jaw bone (see Fig. 2). One challenge was the integration of a water spray nozzle in a very compact volume around the exit pupil of the handpiece tip. This was achieved by using a cylinder with two parallel annular grooves. The first groove serves as path for circulating compressed air and the second for circulating water. The two grooves are connected by three channels that combine the compressed air with the water, which then exits as water spray through three fluidic outlets. We incorporated this cylinder into the handpiece tip, where it connects with the water and air supply channels. The handpiece tip is also accommodating a deflection mirror. To minimize its build volume, the handpiece tip was built using laser powder bed fusion (LPBF).

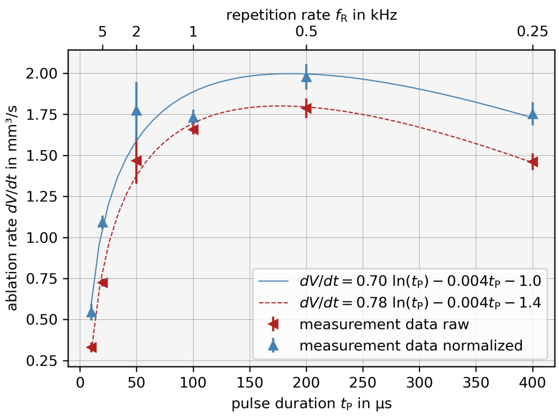


**Fig. 3:** Ablation rate in dependence on the pulse duration and repetition rate in compact bovine bone tissue

# 3 Results and Discussion

## 3.1 Ablation rate

The ablation rate in dependence on the pulse duration and repetition rate is shown in Fig. 3. The mean power was held constant for different ratios of $t_P$ and $f_R$. Due to nonsquare pulse shape, the mean power was lower for pulse durations shorter than 50 µs. Therefore, these values were upscaled for comparability. A maximum ablation rate of $dV/dt = 1.79\,\mathrm{mm^3/s}$ was achieved with a pulse duration of $t_P = 200\,\mu\mathrm{s}$ and a repetition rate of $f_R = 500\,\mathrm{Hz}$. Up to this pulse duration, a higher pulse energy results in a higher ablation rate and depth. For pulse durations longer than 200 µs, the ablation rate decreases. The higher pulse energy does not compensate for the lower repetition rate, resulting in a lower ablation rate of about 14 %. Considering the thermo-mechanical ablation theory, the ablated depth per pulse should increase linearly with increasing pulse energy up to a certain point. With high pulse energy, the ablation per pulse should approach saturation due to plasma or bone debris shielding. In this case, the decreasing ablation rate can be attributed to bone debris that cross the beam path and lead to shielding effects. This would agree with observations of bright process light during ablation at a pulse duration of 400 µs.

## 3.2 Thermal and mechanical impact

For the investigation on the thermal and mechanical impact on the cortical bone tissue, SEM images of the bone sample after laser ablation with five different pulse durations were taken. The microstructure of the cut edge at the top of the laser ablated bore hole was examined. The SEM images are shown in Fig. 4. The structure of the laser ablated zone remains porous with several harversian channels marked by red arrows in Fig. 4 (b). Some cracks are visible at the cutting edges and outside of the laser-ablated zone, which can be explained by the mechanical stress during post-treatment of the samples. For a pulse duration of $t_P = 10\,\mu\mathrm{s}$ and $t_P = 20\,\mu\mathrm{s}$ there were no melted areas observed. The surface structure was free of thermal damage (e.g. carbonization). For a pulse duration of $t_P = 50\,\mu\mathrm{s}$, shown in Fig. 4 (c) a few melted areas with a size smaller than 20 µm can be observed. The melted areas are marked with white arrows. For pulse durations $t_P > 50\,\mu\mathrm{s}$, the number and size of melted areas increases with a maximum size of 30 µm.

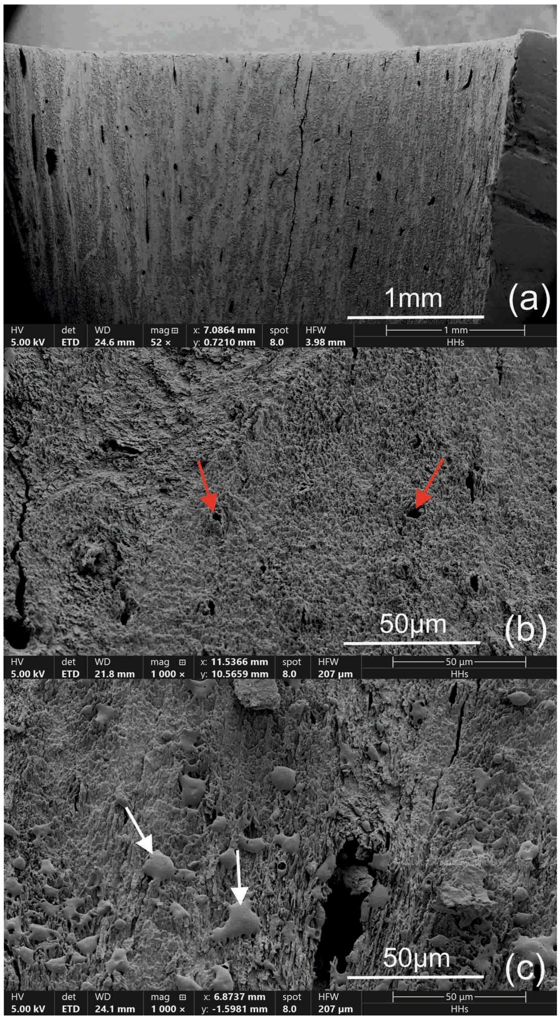


**Fig. 4:** Microstructure of cortical bone tissue after laser ablation using pulsed $CO_2$ laser radiation with a 52x magnification and a pulse width of $t_P = 50\,\mu\mathrm{s}$ (a), with a 1000x magnification and $t_P = 20\,\mu\mathrm{s}$ (b) and $t_P = 50\,\mu\mathrm{s}$ (c). Red arrows indicate open harversian channels, white arrows indicate melted zones.

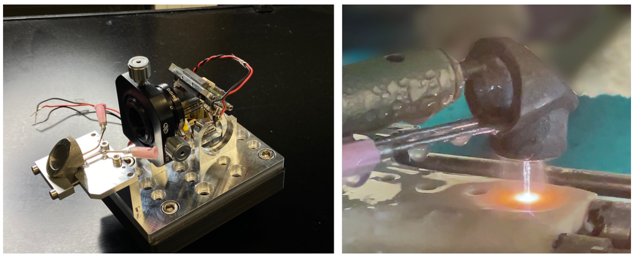

**Fig. 5:** Left image shows the assembled handpiece with all components in an open chassis setup. The right image shows the water spray nozzle being tested while drilling bovine bone samples with $CO_2$ laser radiation.

### 3.3 Applicator technology

A prototype of an applicator for laser drilling in the oral cavity was manufactured and assembled (see Fig. 5). The system was mounted on an optical table and its exit aperture was aligned to the cutting laser. The water spray nozzle was able to generate fine sprays through all three fluidic outlets. First ablation experiments with the setup were performed to investigate whether sufficient cooling is provided and whether comparable results can be obtained with respect to the ablation rate and depth. Using a pulse duration of $100\,\mu s$, a repetition rate of $1\,\mathrm{kHz}$ and the scanning parameters described in Chapter 2, cavities with $3.8\,\mathrm{mm}$ diameter and $8\,\mathrm{mm}$ depth could be drilled. The laser drilled holes were free of visible carbonization. This shows that a compact and functional water spray nozzle could be integrated in the tip of a dental applicator. Nevertheless, further experiments are necessary to evaluate the nozzle design and its effects on the ablation process.

## 4 Conclusion and Outlook

This paper demonstrates a concept for a dental laser drilling system with a fast laser ablation process and a highly-integrated applicator technology which allows treatment in the oral cavity. The relation between ablation rate, pulse duration and repetition rate is investigated for a constant mean power of $29\,\mathrm{W}$ on the bone sample. The ablation rate increases up to a pulse duration of $200\,\mu s$. The maximum ablation rate achieved was $1.79\,\mathrm{mm}^3/\mathrm{s}$ at a pulse duration of $200\,\mu s$ and a repetition rate of $500\,\mathrm{Hz}$. One reason for the decrease of the ablation rate with increasing pulse duration above $200\,\mu s$ is the higher amount of bone debris, resulting in shielding effects that reduce the fluence on the bone surface. For the application of dental implantation, the thermal and mechanical impact on the microstructure of cortical bone is examined. The number of melted zones increases with the pulse duration of the $CO_2$ pulses. Future work is necessary to validate the developed handpiece for laser-based bone ablation in jaw bone. High-power tests must be performed to determine the performance of the optical and mechanical components at the operational limit. The precision of the drill guide must be validated for accurate and reproducible placement of the applicator tip. Additionally, the influence of the drill guide on the water spray should be studied. These studies will further refine the applicator design and provide insight for future improvements of a laser drilling system for treatments in the oral cavity.

**Author Statement**

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