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Accuracy of navigated control concepts using an Er:Yag-Laser for cavity preparation

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***Abstract*—This paper describes a method for measuring the shape accuracy of a cylindrical hole which is created by means of an automatically power-controlled laser system using navigated control. In dental surgery, drills or mills are used for bone treatment. For most patients the use of these instruments is very inconvenient. Furthermore, the bone treatment with rotating instruments can lead to thermal necrosis. Using a laser system could be a good alternative for the patient. The utilization of a laser system could also facilitate bone treatment without any severe thermal damage. An optical navigation system can be used for a safer handling of a laser system. The position and the orientation of the laser handpiece relative to the patient can be calculated. Thereby, the laser can be automatically switched off, if the end of the laser beam does not hit the preoperative planned area. In order to measure the accuracy of such a laser system, we created several cavities in a phantom with a manually guided, automatically power-controlled laser. Afterwards, the deviation between the planned shape and the shape created by manually guided automatically power-controlled laser treatment has been measured. The application of this system showed, that the required accuracy of <1 mm for dental implantology applications, could not be reached.**

I. INTRODUCTION

In dental implantology, a drill is used to prepare the cavities for the insertion of a dental implant. Such a cavity is typically a cylindrical hole of 4 mm to 8 mm diameter and a length between 6 to 15 mm. Before drilling into the patient's jaw (Maxilla, Mandible), the skin (mucosa) has to be removed by a scalpel or tissue punch. This is a standard procedure since cylindrical dental implant has been invented [1],[2]. Since the preparation of cavities using a drill can lead to thermal necrosis of the jaw bone [3]-[6], some research has been done in the area of laser based cavity preparation [7]-[11]. Because of the shape of the drill the bone will be fully ablated and the bottom of the drilled cavity is always a little bit conical (Fig. 1, left).

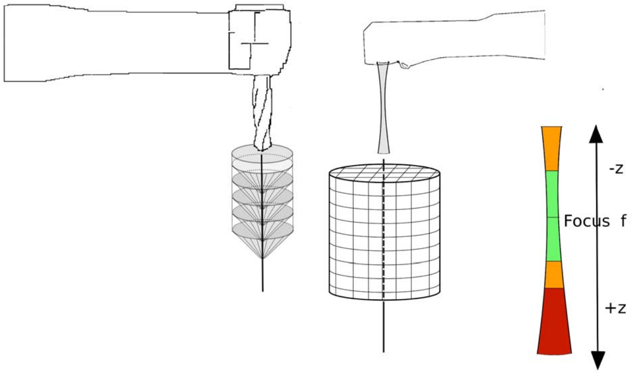

Figure 1: Left: Material removal by cutting drill. Right: Material removal by volume element ablation with a laser.

By means of a laser system, the bone will be cut as single volume-elements (Fig. 1 right). In [12] the influence of implant bed preparation on the osseointegration of titanium implants was analyzed by using an Erbium-YAG-Laser (Er:Yag-Laser) compared with a conventional drilling. It was demonstrated that this laser is suitable for this surgical application. In [13] an overview over the different laser-systems used in oral surgery and implant dentistry is given.

A. *Current Problem*

Using a laser also has some disadvantages. The effect of bone removal with an Er:Yag-Laser depends on so called laser ablation. The bone is heated by the absorbed laser energy. When the energy density is higher than the threshold intensity of the bone, the absorbed thermal energy transforms the material into a molten and vaporized state. The evaporation generates a pressure, which drives the ablated material out of the cut. The advantage of laser ablation compared to mechanical bone removal is, that the resulting thermal energy causes negligible damage to the bone. But if the energy density becomes to low, there will be no laser ablation anymore and because of the increase of thermal energy, the bone will be damaged. The highest energy density for an optimal bone removal lies within the focus f of the laser beam.

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The laser beams diameter increases with increasing distance z to the laser focus. Hence, the energy density along the laser beam decreases with increasing distance z to the focus – as illustrated in Fig. 1, on the right. If the distance of the laser's focus point is too near or too far to the bone, the laser ablation effect changes to a simple bone heating effect that also leads to thermal necrosis. Fig. 2 illustrates the damaging positions of the focus.

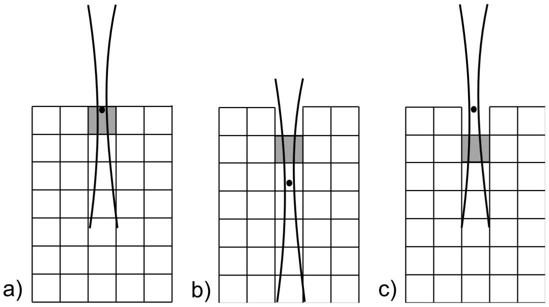

Figure 2: a) The laser beam hits the bone surface in focus – the ablation process occurs. b) The focus of the laser beam lies inside the bone – the energy density is too weak. c) The focus of the laser beam is above the bone surface – the laser ablation effect changes to a simple bone heating and leads to thermal necrosis.

For avoidance of damaging the bone, the laser beam focus always has to be justified on the bone surface. Therefore, the surgeon always has to update the laser handpiece during the ablation process – Fig. 3. Thereby, he has no haptical feedback with a free focused laser handpiece. The removal is executed without physical contact between the instrument and the bone. Therefore, the surgeon has only a visual control over the distance between the laser head and the bone.

In order to overcome these problems, a concept has been published for automatically switching off the laser, if the distance is not in the optimal interval to the bone. This concept, called navigated control, has been published by Stopp et al. [14], [15]. It includes an ablation model of the bone, which is currently calculated during the ablation process. The position of the laser beam focus is calculated at any time interval T_0. The laser beam focus has to be justified on the bone surface; otherwise the laser will be switched off (Fig. 3).

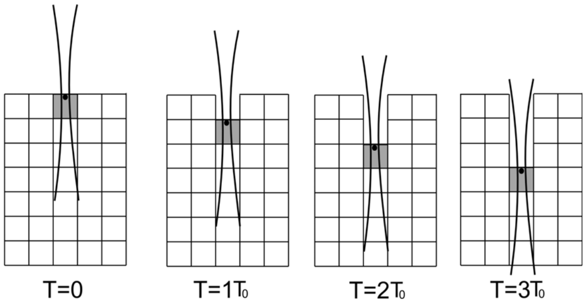

Figure 3: The laser focus has to be at any time focused on the bone surface. Otherwise the laser has to be switched off.

Although, the model in [15] is impressive, it is still unclear which accuracy can be achieved by means of a laser with an automatically controlled shutter.

B. Task Approach

The purpose of the described concept [15] is to enable preparing cavities by the surgeon with the same speed and accuracy as with a conventional drill. The decision to switch the laser off depends on the position and the orientation of the laser handpiece relative to the planned cavities. These will be measured by an optical navigation system. In this paper, we describe the method to measure the shape accuracy of a flattish cylindrical hole that is created by a laser ablation process using the automatic switch off of the laser power. By means of an automatically switched off laser the whole bone inside the planned cavity should be removed and no bone outside the planned area should be removed. The system of the automatically switched off laser must have a shape accuracy of < 1mm outside the planned area and of almost 0 mm inside the planned area.

C. Advantages

Knowing the relationship between the movements of a manually guided laser handpiece, the distance to the bone, and the dynamic of a shutter, the models presented in [15] could be systematically improved.

II. MATERIALS AND METHODS

A. Structure Description

For measuring the accuracy of the manual preparation of a flattish cavity using a dental laser handpiece, we measure position and orientation of handpiece and bone using a stereo camera. Therefore, we use a 3D coordinate measuring camera *cam*. The camera is able to see reflectors, which are mounted at the laser handpiece *tool* and e.g. at a bone structure *pat* (Fig. 4).

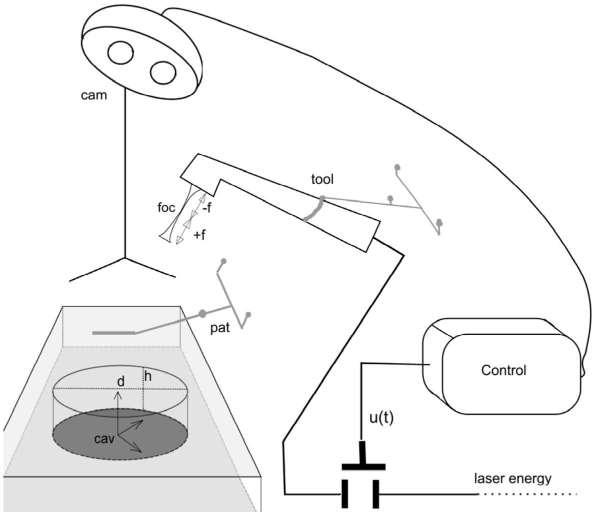

Figure 4: Schematic principle for measuring the accuracy of a cavity prepared by a manually guided, automatically controlled laser ablation

For the description of position and orientation we use the homogeneous transformation matrices. The transformation from the stereo camera to the tool's reflectors is described using:

$$ {}^{cam}\mathbf{T}_{tool} = \begin{pmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0} & 1 \end{pmatrix} = \begin{pmatrix} \mathbf{e}_x & \mathbf{e}_y & \mathbf{e}_z & \mathbf{t} \\ 0 & 0 & 0 & 1 \end{pmatrix} . \qquad (1) $$

In this equation $\mathbf{R}$ is the rotational matrix and $\mathbf{t}$ is the transformation vector. Sometimes it is more efficient to separate the three unit vectors $\mathbf{e}_x$, $\mathbf{e}_y$, $\mathbf{e}_z$ of $\mathbf{R}$ to describe specific directions. Using these formulas, the exact position of the cavity related to the patient can be specified with

$$ {}^{cam}\mathbf{T}_{pat} \cdot {}^{pat}\mathbf{T}_{cav} \qquad (2) $$

and

$$ {}^{cam}\mathbf{T}_{tool} \cdot {}^{tool}\mathbf{T}_{foc} \qquad (3) $$

describe the exact position and orientation of the focus point relative to the handpiece or camera. The cavity has a diameter d and a depth h. The laser has a focus point interval of the height f .

The control box that calculates a control signal $u(t)$ for switching on/off the laser power is also shown in Fig. 4. If $u(t) = 1$, the laser is on. If $u(t) = 0$, the laser is off.

B. *Process Description*

During laser ablation, we always calculate the position of the laser beam focus foc in the coordinate system cav of the planned cavity position:

$$ {}^{cav}\mathbf{T}_{foc} = {}^{cav}\mathbf{T}_{pat} \cdot {}^{pat}\mathbf{T}_{cam} \cdot {}^{cam}\mathbf{T}_{tool} \cdot {}^{tool}\mathbf{T}_{foc} . \qquad (4) $$

This transformation consists of:

$$ {}^{cav}\mathbf{T}_{foc} = \begin{pmatrix} \mathbf{e}_x & \mathbf{e}_y & \mathbf{e}_z & \mathbf{t} \\ 0 & 0 & 0 & 1 \end{pmatrix} . \qquad (5) $$

We should have in mind that these matrices are depending on time, or in case of time discrete signal processing of a sample rate T_0 (Fig. 3)

$$ {}^{cav}\mathbf{T}_{foc} = {}^{cav}\mathbf{T}_{foc}[k] = {}^{cav}\mathbf{T}_{foc}(k \cdot T_0) = {}^{cav}\mathbf{T}_{foc}(t) . \qquad (6) $$

Therefore, we actually have $t[k]$ or $e_z[k]$.
The condition to switch the laser on is fulfilled if:

$$ dis < r \quad \text{with} \quad dis = \sqrt{x^2 + y^2} \quad \text{and} \quad r = d/2 \qquad (7) $$

r is the radius of the cavity and dis is the distance between the axis of the cavity and the position of the laser beam. For calculation of the intersection between the laser beam and the undermost layer or the uppermost layer of the cavity the following equation is solved to get k .

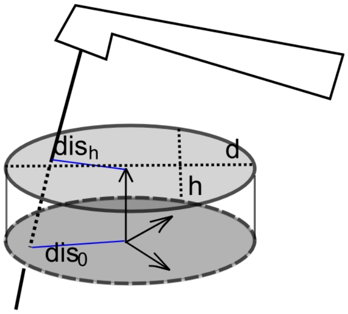

Figure 5: Schematic principle for calculating the condition for controlling the laser

Let $\mathbf{p} = (x \quad y \quad z)^T$ be the intersection point then

$$ \mathbf{p} = \mathbf{t} + k \cdot \mathbf{e}_z . \qquad (8) $$

For the undermost layer there is $\mathbf{p}_z = 0$, for the topmost layer $\mathbf{p}_z = h$. Thus k_0 can be calculated for the undermost layer via

$$ z_t + k_0 \cdot z_{e_z} = 0 \Rightarrow k_0 = -\frac{z_t}{z_{e_z}} \qquad (9) $$

and k_h can be calculated for the uppermost layer via

$$ z_t + k_h \cdot z_{e_z} = h \Rightarrow k_h = \frac{h - z_t}{z_{e_z}} . \qquad (10) $$

Inserting k_0 or k_h in (8), the distance dis_0 to the axis of the implant in the undermost layer and the distance dis_h to the axis of the implant in the uppermost layer can be calculated via

$$ dis_0 = \sqrt{x_0^2 + y_0^2} \text{ and } dis_h = \sqrt{x_h^2 + y_h^2} \qquad (11) $$

The condition for $u(t)$ to switch on/off the laser is:

$$ u(t) = \begin{cases} 0; & dis_0 >= r \vee dis_h >= r \\ 1; & dis_0 < r \wedge dis_h < r \end{cases} \qquad (12) $$

III. EXPERIMENTS

A. *Shape Accuracy of a manually guided laser treatment*

In the following we describe the experiment to measure the shape accuracy of a flattish cylindrical hole, which is created by a freehand guided laser cavity creation using an automatic switch off of the laser power.

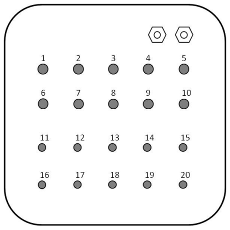

Figure 6: Cavities in the plaster-Phantom: Cavity 1-10 with a diameter of 4.5 mm, Cavity 11-20 with a diameter of 3 mm.

A reproducible measurement setup was constructed to verify the accuracy. A plaster-phantom was used for creating the cavities by the laser. A Digital-Volume-Tomography (DVT) dataset of the plaster-phantom was acquired. Measurement reflectors were attached to the laser handpiece and to the phantom. A navigation system with a NDI Polaris Vicra Camera (NDI, Canada) was used. The experiments were performed with an Er:Yag Laser (KaVo Dental GmbH). The focus radius of the laser is 0.3 mm. The laser operated with a pulse energy of 600 mJ and a pulse frequency of 10 Hz. Inside the laser an additional shutter was installed for control the laser beam. The switching frequency of the shutter was 4 Hz. The shutter was controlled by the control box, which calculates the control signal $u(t)$.

The DVT dataset was registered to the navigation system using an automatic registration algorithm [16]. Afterwards, position and orientation of the laser handpiece relative to the phantom were measured with the optical measurement device. The distance to the implants could be calculated, as described before.

We manually created 20 cavities with the power controlled free focused laser – 10 cavities with a diameter of 4.5 mm, 10 cavities with a diameter of 3 mm – shown in Fig. 6. Following this, the diameters of the lasered cavities were measured with a video-microscope with a magnification of six diameters. The deviation between the planned cavity shape and the lasered cavity shape was detected. For this purpose, we took a reference slab, of which also images were taken with the microscope. Applying an imaging software program (TraumaCad, Voyant Health, Israel), we quantified the shape accuracy. We divided the circle of the planned cavity into 24 angles with

$$\varphi_i = \frac{\pi}{12}(i-1); \quad 1 \le i \le 24 \tag{13}$$

In every image we measured the distance between the center point of the cavity and the outer lasered point at every angle φ_i (Fig 7).

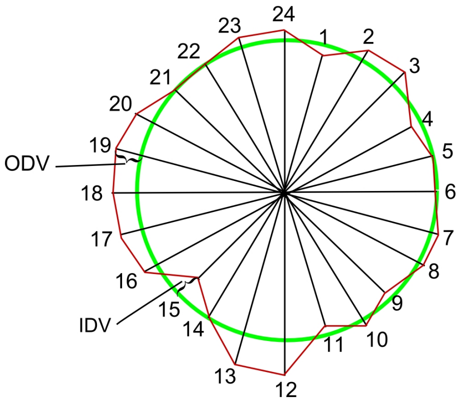

Figure 7: The planned cavity shape is green. The shape created by the laser treatment is red. The distance from the lasered shape to the cavity center is measured at 24 angles.

Therefore we got 24 measured values $(x_i \quad y_i)^T$ with $1 \le i \le 24$. We calculated the deviation (DV) between the planned cavity border and the created cavity border at each measuring point with

$$DV_i = \sqrt{(x_i - r \cdot \cos\varphi_i)^2 + (y_i - r \cdot \sin\varphi_i)^2} \ . \tag{14}$$

We distinguished between the deviating values outside the planned cavity (ODV) and the deviating values inside the cavity and on the cavity's border (IDV).

Furthermore we took images with a Scanning Electron Microscope (SEM) to get an exact visual impression of the lasered cavities.

B. Results

The results of the performed experiment are shown in Tab. 1 and 2. In Tab. 1 the results for the cavities with a diameter of 4.5 mm are shown. For each cavity the means, the standard deviation and the maximum values over all measuring points are indicated. The calculation of these values was separately done for ODVs and IDVs. The mean, the standard deviations, and the maximum over all measured points for the ODVs and IDVs are indicated, too. In the last line the mean for the standard deviation and the maximum of all cavities were calculated.As expected, the values for the ODV are significantly higher than the IDV. The maximal value of IDV lies in the range of sub millimeters. The ODV is worse. The mean over all cavities is 0.31 mm with a standard deviation of 0.19 mm. The maximum over all cavities is 0.75 mm. In Tab. 2 the results for the cavities with a diameter of 3 mm are shown. The means and the maximum values of all ODVs and IDVs are indicated here, too. Inside these small cavities, the material was always completely removed. Hence the IDV is 0 mm. The mean of the ODVs over all cavities is 0.5 mm with a standard deviation of 0.17. The absolute maximum is 1.0 mm; the mean maximum over all cavities is 0.86 mm.

The result is, that for the cavities with a diameter of 4.5 mm, the mean maximum from the ideal radius to the lasered radius is 0.75± 0.25 mm. Cavities with a diameter of 3 mm have a mean maximum of 0.86± 0.12 mm. Therewith, there could only be achieved an accuracy of 1.5 ± 0.50 mm for the larger cavities and 1.72 ± 0.24 mm for the smaller ones. This accuracy is too less for creating cavities for dental implants. This finding must be discussed and has to be verified in further experiments.

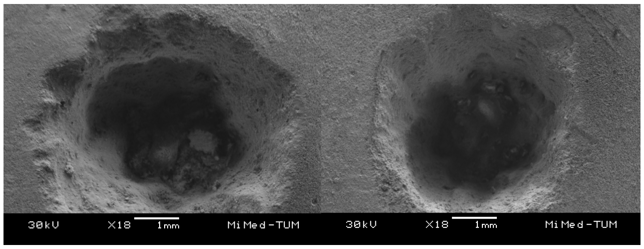

Figure 8: Images of lasered cavities taken with a Scanning Electron Microscope

In Fig. 8 two images of lasered cavities are shown exemplarily, taken with the SEM.

The focus spot of the laser beam can be seen very clearly. It can also be seen, that the circle of a cavity can be lasered very even, if the laser is power controlled. Inside the cavity the material is removed completely. Outside the cavities several laser shots out of the circle are seen.

TABLE I
RESULTS FOR CAVITIES WITH DIAMETER OF 4.5 MM

	ODV (mean)	ODV (std)	ODV (max)	IDV (mean)	IDV (std)	IDV (max)
Cavity 1	0.31	0.27	0.95	0	0	0
Cavity 2	0.33	0.19	0.65	0.05	0	0.05
Cavity 3	0.09	0.08	0.25	0.05	0	0.05
Cavity 4	0.19	0.11	0.45	0	0	0
Cavity 5	0.27	0.18	0.65	0.05	0	0.05
Cavity 6	0.39	0.21	0.95	0.05	0	0.05
Cavity 7	0.35	0.15	0.75	0	0	0
Cavity 8	0.34	0.26	0.85	0.05	0	0.05
Cavity 9	0.32	0.28	0.95	0	0	0
Cavity 10	0.53	0.21	1.05	0	0	0
	0.31	**0.23**	**0.95**	**0.05**	**0**	**0.05**
$\frac{1}{10}\sum_{i=1}^{10} i$	**0.31**	**0.19**	**0.75**	**0.05**	**0**	**0.05**

TABLE II
RESULTS FOR CAVITIES WITH DIAMETER OF 3 MM

	ODV (mean)	ODV (std)	ODV (max)	IDV (mean)	IDV (std)	IDV (max)
Cavity 11	0.46	0.19	0.8	0	0	0
Cavity 12	0.53	0.15	0.9	0	0	0
Cavity 13	0.51	0.19	1.0	0	0	0
Cavity 14	0.53	0.22	1.0	0	0	0
Cavity 15	0.57	0.21	1.0	0	0	0
Cavity 16	0.45	0.15	0.8	0	0	0
Cavity 17	0.49	0.16	0.8	0	0	0
Cavity 18	0.50	0.13	0.7	0	0	0
Cavity 19	0.46	0.13	0.7	0	0	0
Cavity 20	0.55	0.15	0.9	0	0	0
	0.5	**0.17**	**1.0**	**0**	**0**	**0**
$\frac{1}{10}\sum_{i=11}^{20} i$	**0.5**	**0.17**	**0.86**	**0**	**0**	**0**

IV. DISCUSSION AND CONCLUSION

In this article a method to measure the shape accuracy of a flattish cylindrical hole, which was created by a laser ablation process using an automatic switch off of the laser power, was presented. We wanted to know which accuracy can be achieved to create a manually guided lasered cavity by using a power controlled laser system. For this purpose, we realized an experimental setup including a navigation system for measuring the position of the patient relative to the laser handpiece and a control box, which calculated the condition for switching on or off the laser power. We took a plaster-phantom and created 20 cavities with this system.

We found out, that the required accuracy of <1 mm, which is sufficient for dental implantology applications, could not be reached. Analyzing the result, there are two main points which have to be clarified in further works: First, we didn't mind the focus radius of the laser beam. The condition for switching on or off the laser should not depend on r - the radius of the cavity (12) - but on $r - r_{lf}$, where r_{lf} is the focus radius of the laser beam. Second, the switching frequency of the shutter in the laser is 4 Hz. That is less than the half of the laser pulse frequency of 10 Hz. Until the shutter is closed, 1 or 2 laser pulses more could be released. However, the circle of the cavities could be lasered very even with this system, as we could see in the SEM images.

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