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Basic concepts of optical measuring of bone thickness with IR-Beam

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Abstract—This paper describes a new concept for measuring bone thickness via optically analyzing of hard tissue. In many surgical disciplines effecting bone treatment, like oral and maxillofacial surgery or otolaryngology, the knowledge of existing bone material is very important in order not to hurt anatomically sensitive structures. The existing bone material can be determined preoperatively using imaging procedures. However, the surgeon has no information about the residual bone thickness during the intervention. As a consequence of this, the distance between the tip of his instrument and sensitive structures is also unknown. Therefore, it would be very useful, if the bone thickness could be measured concurrently to the bone ablation. In this work, bone was irradiated with IR-Light and the reflection was detected. It would be examined, if there was an interrelation between bone thickness and reflection and how it could be measured. The results of the experiments show, that by means of this method it is possible to detect different bone thicknesses for a bone thickness < 1 mm.

I. Introduction

The dental implantology is the conventional method for surgical treatment of lost teeth. Usually a mechanical instrument like a drill is used for preparing cavities for the insertion of dental implants. Also worth mentioning would be the utilization of laser in implant dentistry [1]. The whole process of implanting can be divided into different steps: the preoperative surgery planning, the surgical intervention, a phase for healing and the prosthetic restoration.

In surgery planning the position and orientation of the implant is accomplished according to the bone volume, bone density, in consideration of osseointegration and especially in consideration of adjacently sensitive anatomical structures like nerves. In surgical intervention, first the mucosa is removed by a scalpel or tissue punch. Afterwards, a pilot drilling is performed with a small drill. This pilot drilling defines position, orientation and depth of the cavity. It is very important for the surgeon to know the distance to the closest sensitive structure. Otherwise he could hurt a sensitive structure. The amount of bone removal before a sensitive structure is at risk could be identified by preoperative imaging techniques like X-ray. However, the surgeon has no information about the residual bone thickness during the intervention. Hence, being able to measure how many millimeters of bone are left before a sensitive structure could be hurt, would be very helpful while drilling.

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A. Pre- and postoperative measurements of bone thickness

The bone thickness can be measured pre- and postoperative using 2D and 3D imaging procedures. The standard technique in implantology is the 2D orthopantomography (OPG) [2]. A 3D procedure for measuring bone thickness is the computed tomography (CT) [3],[4]. A newer imaging procedure in dental implantology is the digital volume tomography (DVT). It is used for the surgical planning, as well as CT.

B. Optical analysis for tissue

In optical tissue analysis, waves of light are inserted into tissue. Information about the tissue is gained by analyzing the dispersion coefficient, the absorption coefficient and the attenuation coefficient [5]. There are several methods for the optical analysis of tissues in the state of research. However, the optical-coherence tomography (OCT) is the method that is widely used in clinical routine for ophthalmological examination [6]. Measuring of the light reflection of different types of tissues is based on white light interferometry [7]. Different types of tissues can be detected because of the different intensity of the reflected light. The position of tissues can be detected by different reflection time. Another method for optical analysis of tissues is the near-infrared fluorescence imaging (NIRF) [8],[9]. In diffuse optical tomography (DOT), transmitted optical radiation is detected from different sides of a body. A 3D image should be recovered, from this detection This is a mathematically inverse problem, which can be solved with different methods [10]-[12].

C. Current Problem

The surgeon has no information about the residual bone thickness during the bone ablation. Fig. 1 illustrates the problem in implantology. The nerve N. alveolaris passes through the lower jaw. While drilling, the distance to the nerve decreases. The risk of hurting the nerve increases with decreasing distance between drill tip and nerve. Nevertheless, the surgeon does not know the currently remaining distance during the intervention. A preoperative taken X-ray, frequently an OPG, is used for orientation (Fig.

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2). But the information in an X-ray is static. It takes several minutes (which is a lot of time) and is highly exposed to radiation to take an X-ray image during the intervention.

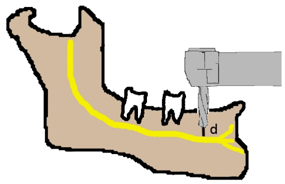

Figure 1: A pilot drilling in the implantology. If the distance d becomes to low, the drill can hurt the nerve.

In order to get information about the residual bone during the treatment, an optical analysis of the bone tissue can be a good alternative. As far as we know, there is no clinically established system for optically analyzing of hard tissue.

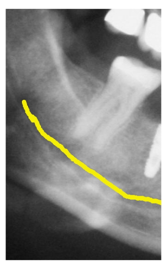

Figure 2: Part of an OPG. Under the teeth the nerve is drawn in the picture.

D. *Task Approach*

In this paper we describe a new method for the optical analysis of thin hard tissue structures with infrared light. We want to examine if it is possible to measure the thickness of bone just by measuring the reflected radiation. Therefore we take several specimens of bone tissue with different thickness. We irradiate these bone fragments with monochromatic light and detect and analyze the reflected radiation. We investigate the effect of different wavelength, the influence of the adjacent tissue and the influence of the depth of a cavity.

E. *Advances*

Identify the bone thickness based on the reflected radiation is a basic requirement for being able to develop a system for an optical measuring of the residual bone thickness during surgical intervention.

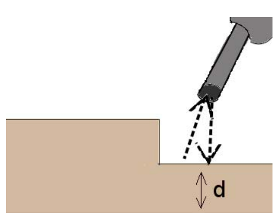

Figure 3: The residual bone thickness should be measured with a sensor placed at the tip of an instrument.

Consequently, the risk of damaging sensitive anatomical structures during interventions can be decreased. Furthermore, measuring of bone thickness with infrared light is a non invasive method. For this reason, this measuring is a gentle method for patients compared to X-ray imaging.

II. METHODOLOGY

A. *Structure Description*

The irradiations of the bone with monochromatic light were done with a grating monochromator (Fig 4 (1)). A grating monochromator disperses white light into quasi-monochromatically light. In addition, the following devices were parts of our measurement station: a camera for detecting the reflected illumination (Fig 4 (3)), an x,y – table (Fig. 4 (5)) for the precise positioning of the bone specimens (Fig. 4 (4)) and a computer for controlling the devices and for evaluation (Fig 4 (2)).

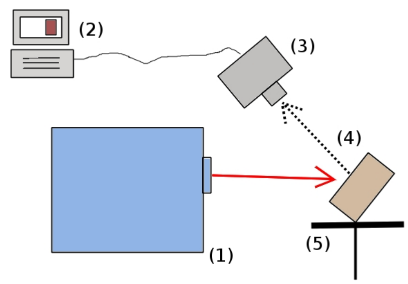

Figure 4: Schematic view of our measurement station: (1) Monochromator, (2) computer station, (3) camera, (4) bone specimen, (5) x,y-table.

B. *Process Description*

In our experiments we illuminated the different bone specimens with monochromatic radiation. We detected the reflected radiation and analyzed the detected images with a computer software. Our analysis is based on the detected luminosity. In order to facilitate comparisons, we took a region of interest (ROI) in every detected image. These ROIs were created in the centers of the images where high luminosities were detected. Inside these ROIs we calculated the mean of the color-averaged intensity. Let

$$\Omega = \{(x, y) \in \mathrm{IN} \times \mathrm{IN} \mid 1 \le \mathrm{x} \le \mathrm{w}, 1 \le \mathrm{y} \le \mathrm{h}\} \qquad (1)$$

be the set of all pixels of the image with a width of w and a height of h. Then the ROI can be defined with

$$ROI = \left\{(x,y) \in \Omega \mid \frac{w + w_{ROI}}{2} \le x \le \frac{w + w_{ROI}}{2}, \frac{h - h_{ROI}}{2} \le y \le \frac{h + h_{ROI}}{2}\right\} \qquad (2)$$

where w_{ROI} is the width of the ROI and h_{ROI} is the height of the ROI.

The color values are defined by

$$I(x, y) = \begin{pmatrix} r_{x,y} \\ g_{x,y} \\ b_{x,y} \end{pmatrix} \in N^3 \quad \forall (x, y) \in \Omega \qquad (3)$$

with $N = \{n \in \mathrm{IN} \mid 0 \le n \le 255\}$.

Therewith, the color-averaged intensity can be calculated via

$$I_{grey}(x,y) = \frac{r_{x,y} + g_{x,y} + b_{x,y}}{3} \in N \quad \forall (x,y) \in \Omega \,. \tag{4}$$

In order to compare the detected values, we calculated the mean of every ROI with

$$I_{grey,mean}(x,y) = \frac{\sum_{(x,y)\in ROI} I_{grey}(x,y)}{w_{ROI} \cdot h_{ROI}} \,. \tag{5}$$

III. Results

A. Reflection behavior of bone

First, we examine the reflection behavior of bone. We wanted to prove the possibility of distinguishing different bone thicknesses by measuring their reflections. Therefore, we took 4 different bovine bone fragments. Every fragment had a thickness of 3 mm with different milling grooves. The residual bone thickness in the milling grooves was between $d = 0.15$ mm and $d = 1.5$ mm.

In a preliminary test, we determined that a wavelength of λ = 685 nm has a good transmission rate in bone. Hence, in our first experiment we chose this wavelength. We irradiated the bones with the monochromatic light and detected the reflections with the camera. Afterwards, we analyzed the images.

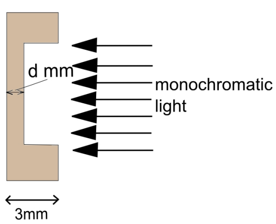

Figure 5: Illumination of a bovine bone fragment. Every bone specimen has a thickness of 3 mm but with different milling groves. The residual bone thickness d is in a range of 0.15mm up to 1.5mm.

TABLE I
RESULTS FOR FIRST BONE SPECIMEN

Residual bone thickness (mm)	Averaged detected intensity
0.15	139.8
0.20	145.1
0.45	170.9
0.53	182.5
1.06	187.6
1.50	191.9

TABLE II
RESULTS FOR SECOND BONE SPECIMEN

Residual bone thickness (mm)	Averaged detected intensity
0.36	159.3
0.49	176.1
0.63	180.5
0.68	187.2
0.82	190.0
0.90	192.1
0.98	207.0
1.1	219.0

Tab. 1 and Tab. 2 show the results for two bone fragments. As expected, the averaged intensity increases with increasing bone thickness, because less illumination is transmitted. This was observed at every bone specimen. However, the absolute values of averaged detected intensity were not comparable between the different bone fragments.

B. Influence of the used wavelength

In this experiment we investigated the influence of the wavelength of the measurement of the bone thickness. We chose four different residual bone thicknesses: $d = 0.36$mm, $d = 0.49$mm, $d = 0.98$mm and $d = 1.10$mm. We irradiated these specimens with monochromatic light in a range between λ = 450 nm and λ = 2050 nm and an increment of λ = 50 nm. We evaluated the detected images by calculating and comparing the mean of the color-averaged intensities.

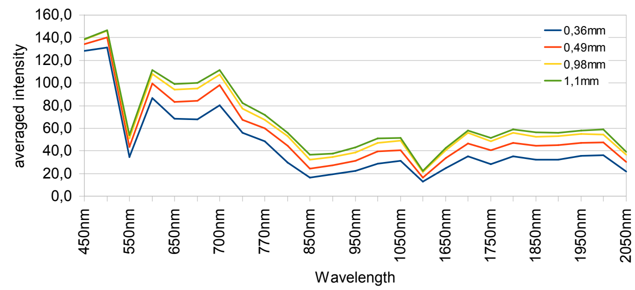

Figure 6: Diagram of the variation of the wavelength: blue line is the residual bone thickness of 0.36 mm, red line is the residual bone thickness of 0.49 mm, yellow line is the residual bone thickness of 0.98 mm and green line is the residual bone thickness of 1.1 mm.

The diagram in Fig. 6 shows, that a small residual bone thickness causes in a low averaged intensity and a big bone thickness causes in a high averaged intensity for every wavelength. Furthermore it was discovered that the largest span, and therefore highest contrast, between the different residual bone thicknesses is in the range from λ = 600 nm to λ = 770 nm and from λ = 1850 nm to λ = 1950 nm.

C. Influence of soft tissue

In the first experiments, that examined the reflection behavior of bone, the adjacent medium was air. In this experiment the reflection behavior of bone tissue in front of soft tissue was investigated. Therefore soft tissue was attached behind the bone.

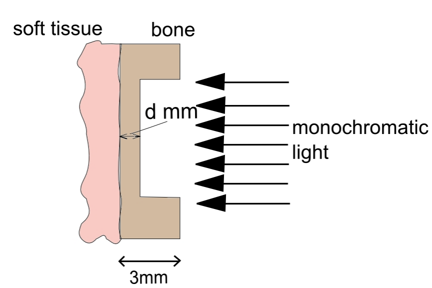

Figure 7: Illumination of a bovine bone fragment with soft tissue. Every bone specimen has a thickness of 3 mm, but with different milling groves. The residual bone thickness d is in a range from 0.15 to 1.1 mm. The soft tissue has a width of 25 mm.

The construction of a bone fragment with the attached soft tissue is illustrated in Fig. 7. Bone specimens with d residual bone thickness of $d = 0.36$ mm, $d = 0.49$ mm, $d = 0.98$ mm and $d = 1.1$ mm were used. The thickness of the soft tissue was about 25 mm. The applied wavelengths were $\lambda = 685$ nm, $\lambda = 770$ nm and $\lambda = 1900$ nm. For every wavelength an increase of the residual bone thickness leads to an increase of the averaged intensity, which is shown in Fig. 9. The soft tissue does not inhibit the measurements of the residual bone thickness.

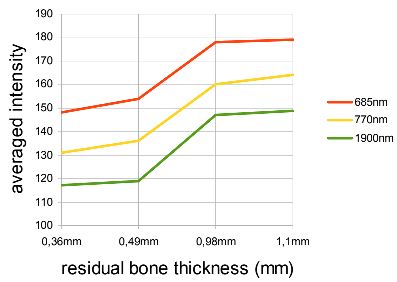

Figure 8: Diagram of the results of the examination of the influence of soft tissue.

D. *Influence of cavities and hollows*

In order to be able to evaluate the applicability of an intraoperative optical measurement system, the influence of cavities and hollows had to be examined. We analyzed the influence of the depth of the cavity.

The depth of the cavities varied between 2 mm and 6 mm with a step size of 1 mm. The diameter was 4 mm and the residual bone thicknesses were $d = 0.3$ mm and $d = 0.5$ mm (Fig. 9).

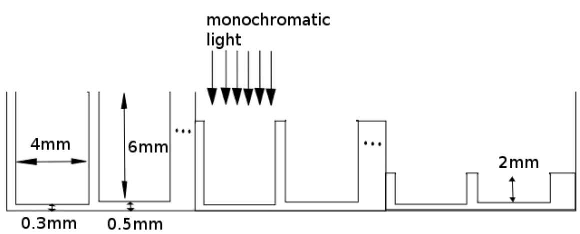

Figure 9: Bone specimens with different cavity depths and residual bone thickness.

The bone was illuminated with radiation of three wavelengths: $\lambda = 685$ nm, $\lambda = 770$ nm and $\lambda = 1900$ nm, as already used above. The detected images were analyzed. The results show that the depth of the cavity had no considerable influence on the detected intensity until a depth of 6 mm. The different residual bone thicknesses were also recognized until a depth of 6 mm. By means of a wavelength of $\lambda = 1900$ nm the different residual bone thicknesses were also recognized with a cavity depth of 6 mm.

IV. Conclusion

In this paper a new method for optical analysis of hard tissue was presented. The aim of this work was to examine, if differences in various residual bone thicknesses can be detected by analyzing their reflected radiation. We were able to show that it is possible for bone thicknesses $d < 1$ mm. We determined the suitable wavelengths for these measurements in the range from $\lambda = 600$ nm to 770 nm and from $\lambda = 1850$ nm to $\lambda = 1950$ nm. Therefore, in the following experiments we used wavelength of $\lambda = 685$ nm, $\lambda = 770$ nm and $\lambda = 1900$ nm. Therewith, we showed that various bone thicknesses could also be detected, if there was soft tissue behind the bone. The soft tissue transmitted the radiation very well. In that way the differences in the reflected radiation could be measured just as well as within the air. At last we showed that measurements are possible up to 5 mm from the outside of the cavity. They are even possible up to 6 mm by using a wavelength of $\lambda = 1900$ nm.

Based on the results of this work, we want to carry out more examinations in optical analysis of hard tissue. The aim of the whole project is to develop an instrument for measuring the residual bone thickness concurrently to the bone ablation. Hence, the next step is to evaluate the influence of different tissue characteristics of bone.

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