Laser-Tissue Interaction of Pump-Probe Elastography (PPE) on Human Teeth

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ABSTRACT

The utilization of lasers in dentistry expands greatly in recent years. For instance, fs-lasers are effective for both drilling and caries prevention, while cw-lasers are useful for adhesive hardening. A cutting-edge application of lasers in dentistry is the debonding of veneers. While there are pre-existing tools for this purpose, there is still potential for improvement. Initial efforts to investigate laser assisted debonding mechanisms with measurements of the optical and mechanical properties of teeth and prosthetic ceramics are presented. Preliminary tests conducted with a laser system used for debonding that is commercially available showed differences in the output power set at the systems console to that at specified distances from the handpiece. Furthermore, the optical properties of the samples (human teeth and ceramics) were characterised. The optical properties of the ceramics should closely resemble those of teeth in terms of look and feel, but they also influence the laser assisted debonding technique and thus must be taken into account. In addition first attempts were performed to investigate the mechanical properties of the samples by means of pump-probe-elastography under a microscope. By analyzing the sample surface up to 20 ns after a fs-laser pulse impact, pressure and shock waves could be detected, which can be utilized to determine the elastic constants of specific materials. Together such investigations are needed to shape the basis for a purely optical approach of debonding of veneers utilizing acoustic waves.

Keywords: Elastography, Microscopy, Pump-Probe, Dentistry, Tooth, Laser, Femtosecond

1. INTRODUCTION

Until now, the most common way to prepare teeth has been mechanical drilling, but it is often noisy and can cause more damage to the tooth than necessary. In recent years, lasers have been used in dentistry to improve treatment. However, while there have been many studies showing the potential benefits of laser treatment, there is still uncertainty about the damage it may cause to teeth.[1,2] The first attempts to use lasers in dentistry were made in the 1960s, but they were largely unsuccessful due to the long pulses of the lasers, which caused thermal and structural stress to the teeth and pulp and discomfort and pain to the patient.[3] However, with the introduction of improved laser systems that have shorter pulses and better energy control, laser treatment in dentistry has become more comfortable for patients.[4,5]

Recent studies have shown that pulsed lasers can be used to gently remove dental prostheses.[6] Dental prostheses are often fixed with a high-strength adhesive, so removing them with conventional dentistry methods can be difficult and may damage the teeth. It has been proposed, that by using pulsed lasers focused into the thin layer of adhesive, the veneer can be removed without causing significant damage to the teeth.[7]

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This preliminary study outlines the initial findings as a baseline to better understand the mechanism of a laser-assisted method of removing veneers. The approach also investigate the use of acoustic waves that travel across the interface between the ceramic, adhesive, and tooth. Thereby, the waves should loosen the adhesive and lead to an easy detaching of the ceramic. The study incorporates advanced methods for measuring the mechanical[8] and optical properties of both the teeth and ceramics, along with initial usage of state-of-the-art debonding system, to find out whether the process is related to a confined energy situation or a different condition during the debonding process.

2. MATERIAL AND METHOD

2.1 Material

The samples (prepared at the Department of Prosthetic Dentistry at the University of Cologne) contain different cross section cuts of human teeth cut from above the pulp and with the pulp cove in the middle (Figure 1A). Additionally, samples of standard restorative materials for veneers of different types were provided from different companies (Ivoclar and Variolink). The veneer materials have different coloring, which helps to match the color of the remaining teeth (Figure 1B).

Figure 1: A: tooth sample, cross section without and with pulp cavity; B: ceramic materials, various manufacturer, materials and colors

2.2 Laser System for Debonding

The laser system (Lightwalker AT/AT-S, Fotona, Gruibingen, Germany) contains two high-power laser sources (Er:YAG and Nd:YAG) and an artificial mirror arm (OPTOflex, Fotona) to transfer the light energy to a specified application handpiece. The various handpieces provided give the user all possibilities for laser dental treatments, in this study the handpiece H02-N (Fotona) was used. It is used as a non-contact, 90-degree handpiece for the Er:YAG laser, and gives a 0.9 mm spot size diameter at the focus and is additionally equipped with an air/water spray nozzle.

Table 1: Parameter of laser system (Lightwalker AT/AT-s, Fotona):[9]

Laser type	**Er:YAG laser**
Wavelength	2940 nm
Output energy per pulse	5 to 1500 mJ in 5 mJ - steps
Max. Fluence	48 J/cm^2
Pulse repetition rate	2 to 50 Hz
Max. average power	20 W
	Super Short Pulse (SSP, 80 μs)
	Micro Short Pulse (MSP, 100 μs)
pulse width mode	Short Pulse (SP, 300 μs)
	Long Pulse (LP, 600 μs)
	Very Long Pulse (VLP, 1000 μs)

During treatment the handpiece is positioned by the user per hand and the held in place with support of the OPTOflex arm. For debonding the veneer a scanning pattern is often used and therefore the handpiece and the spot on the tooth has to be moved by the operator. To determine the power being applied to the target surface and to better understand the system's interaction with the material, power measurements were taken at various distances from the handpiece and at the various emission modes respectively pulse durations, using a power meter[10] (FieldMaxII Laser power Meter, Coherent, Saxonburg, Pennsylvania, USA).

2.3 Optical Characteristics of Ceramic Material

The optical properties of the samples were measured with two setups. For measuring the diffuse transmission and remission of the ceramics an integrating sphere setup was used, for measuring the absorption/reflection of the teeth in the range of 500 - 1000 nm a hyper-spectral imaging (HSI) system (TIVITA Tissue, Diaspective, Pepelow, Germany) was used. Figure 2A shows the schematic of measuring the diffuse transmission, which describes all light scattered by the sample of the excitation after passing through the sample. The schematic of measuring the remission of the samples is shown in Figure 2B. The remission describes the diffuse reflection of a sample, to get a normalized result of all samples a reference measurement was done with a white ceramic reference sample.
To measure the absorption/reflection the teeth were placed on a white background and illuminated by a specified white light. The illuminated sample area then gets imaged by a hyper-spectral camera in the VIS/NIR range (spectral range 500 - 1000 nm).[11] With the captured reflection by the camera in combination with the reference background the absorption of the samples can be calculated by the software (Figure 2C).

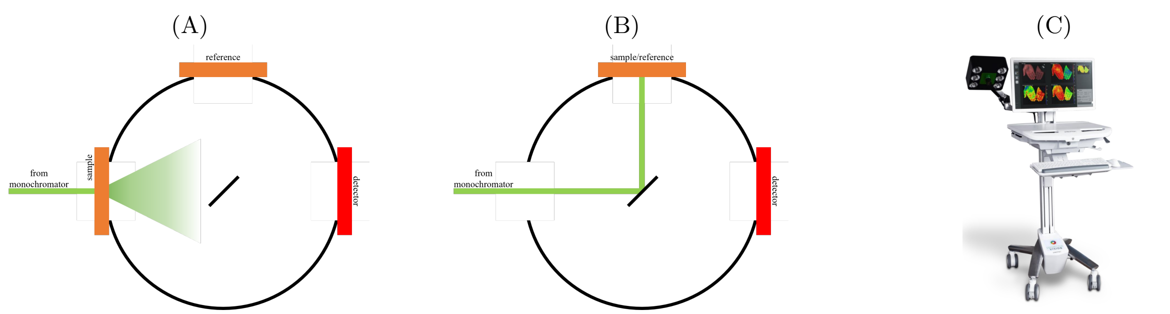

Figure 2: A and B: schematic of integrating sphere setup for diffuse transmission and remission measurement; C: HSI-setup

2.4 Mechanical Characteristics of Ceramic Material

To determine the mechanical properties of the materials a pump-probe elastography (PPE) microscope was used. It uses a fs-laser source (1040 nm, 385 fs, 100 kHz, up to 30 μJ) (Spectra-Physics, MKS Instruments, Andover, Massachusetts, USA), a single-pulse is then split into a high energy 1040nm-pulse ("pump") and a 520nm-pulse ("probe"). A microscope objective focuses the pump-pulse onto the sample, the ablation generates a shock wave traveling into the vicinity around the impact. Meanwhile, the probe-pulse is time delayed up to 20 ns to illuminate the area around the impact by Köhler illumination. The whole illuminated area gets imaged by a sCMOS camera above the microscope objective. Figure 3A and B shows the schematic and the real setup of the pump-probe elastography system. The system takes three images – background (before impact), delayed (after set delay time), afterwards (1 sec after impact, can be used to observe the material and ablation). The background and delayed image are used to calculate a difference image, which should show the laser induced wave front. By measuring the distance from front to front of the wave through the impact area, you get the diameter in pixels. By taking the pixel size of the camera and the magnification of the objective into account the size of a single pixel can be calculated in microns. The radius of the induced acoustic waves (Figure 3C) can be used to calculate the shear (G) and bulk modulus (K), which can then be used to calculate Young's modulus of the material.[5,8,12]

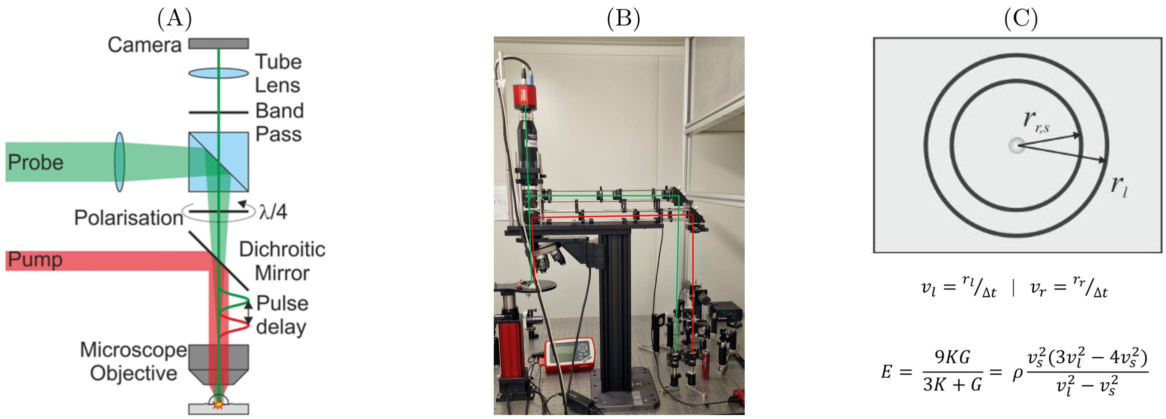

Figure 3: (A and B) schematic and real setup of the pump-probe elastography; (C) radius measurement and equations

3. RESULTS AND DISCUSSION

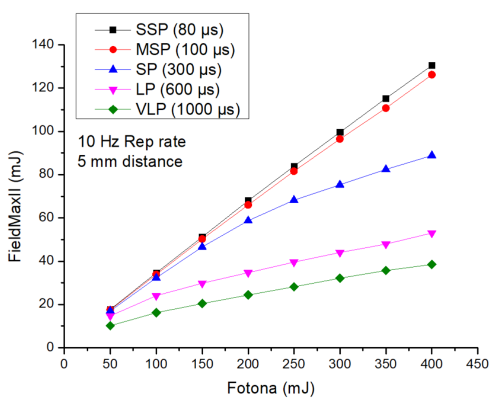

Figure 4: measured power at 5mm from handpiece

Figure 4 displays the measured laser power at varying emission modes (pulse durations) at a distance of 5 mm from the handpiece. The two shortest pulsed modes, super short pulse (SSP) and micro short pulse (MSP), show a linear behavior when comparing the laser power set on the device and the measured power at all distances. Thereby, the measured power ranges from 20 mJ to 140 mJ showing a reduction of 70 % to 35 %. The other modes, SP, LP, and VLP, display a flattening behavior with higher set power. Regarding the distance between handpiece and power meter detector show no significant change of measured power, although there is a significant drop of the measured power calue when longer pulse durations are used.

Figure 5A to D show the diffuse transmission and remission of the veneer ceramics material, respectively. Each graphic contains data from up to 5 independent samples of the stated material, and the data does not show significant variation across the entire 400 nm to 1100 nm spectra. However, significant differences arise when comparing the materials to each other, even between those from the same manufacturer. A closer look at the graphs in 5A and B reveal dips at 520 nm and 650 nm, which are shown by literature for zircon ceramics.[13] The graphs in 5B and D also show specific behavior between 900 nm and 1000 nm. Figure 6 show the reflection of the human teeth measured with the HSI system. The data of the human teeth (Figure 6 exhibits substantial variations in optical properties between the teeth themselves. This could be attributed to measurement errors arising from the translucence of the teeth and the white background used.

In Figure 7A to D the process of PPE-measurement is depicted. The plot Figure 8 shows measurements at six positions of the sample across the yellow line in Figure 7D. The x-axis is thereby calculated from pixel values to actual distances in μm. The area and graph between the red lines (distances -20 to 20 microns) correspond to the area of laser impact. However, the wave front is seen under the red arrow and measures in at around $\boldsymbol{r = 65\ \mu m}$. This corresponds, following the equations in Figure 3C, to a speed of wave of $\boldsymbol{v = \frac{65\ \mu m}{20.2 ns} = 3{,}218}$ **km/s or 3.318 m/s**. Altogether the six graphs show high reproducibility and the wave front appear to be on the same radius.

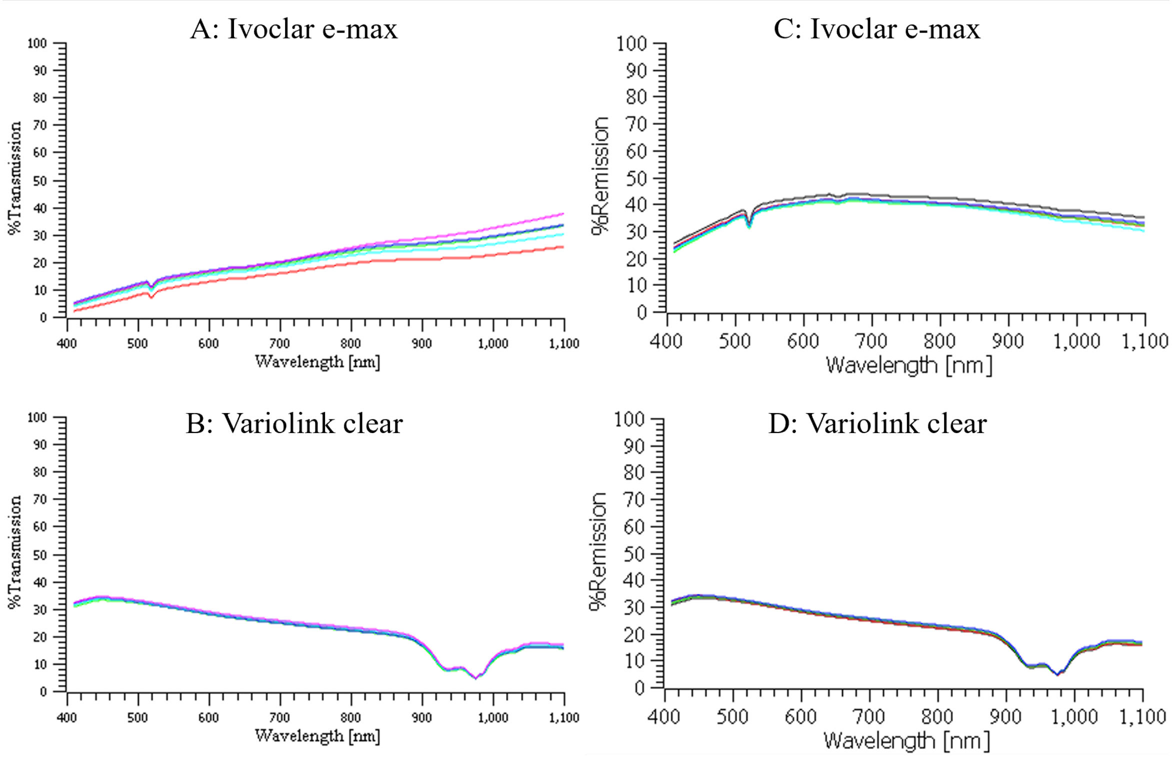

Figure 5: Results of the measurements of optical properties
(A and B) diffuse transmission of veneer material (n = 4-5); (C and D) remission of veneer material (n = 4-5

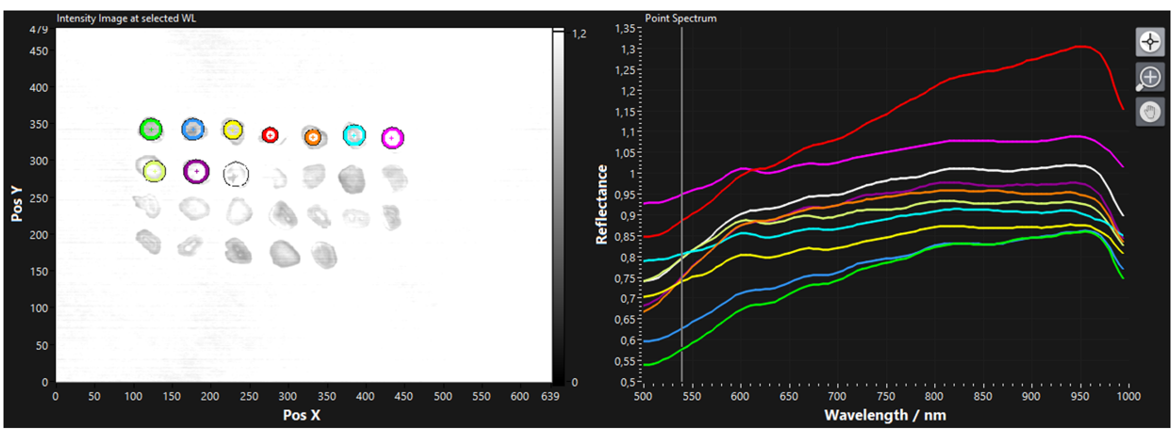

Figure 6: Results of the measurements of absorption/reflection of human teeth

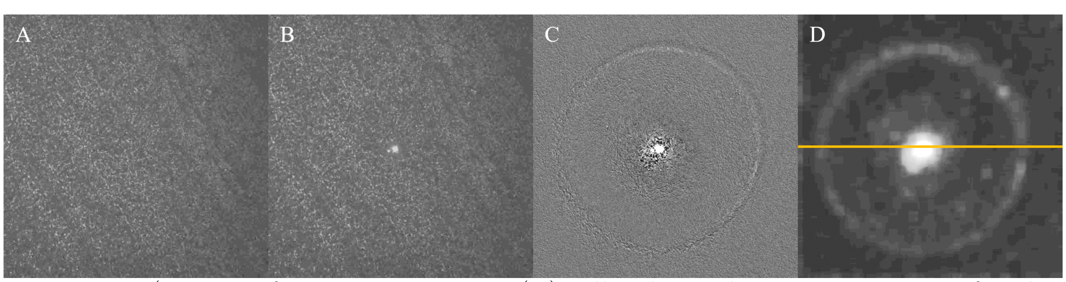

Figure 7: (Process of PPE measurement, (D) yellow line indicates measurement for plot

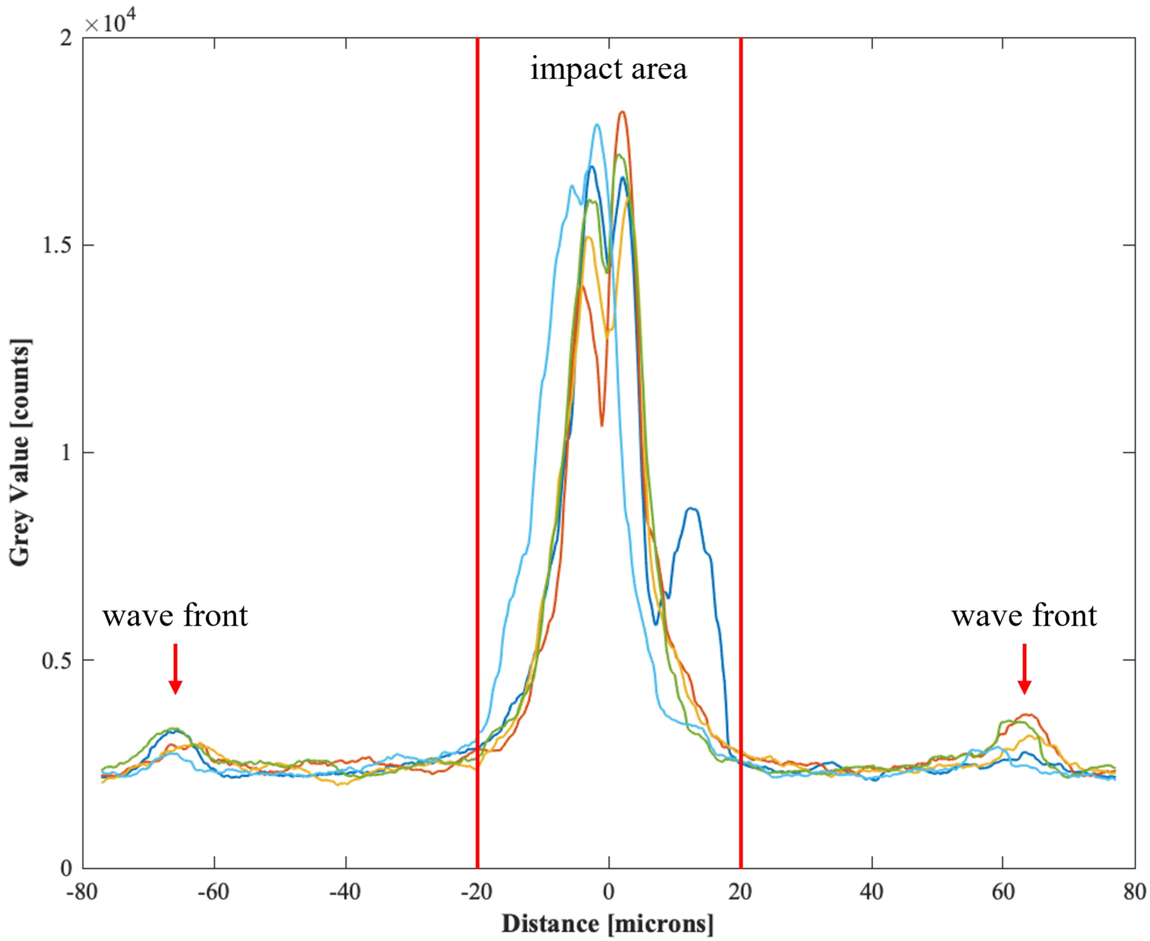

Figure 8: measurement of wave front (n = 6)

4. SUMMARY

The application of pulsed lasers in dentistry is advancing quickly, either to ablate material or debond prosthetic. The laser system used for debonding shows a constant power output from the handpiece at different distances to the object but different to the console value. Comparing the human teeth with restorative ceramics showed significant differences in absorption and reflection of light. The measurement of the mechanical properties revealed that it is possible to generate acoustic waves on human teeth and to calculate elastic properties.
Future work is concentrating on the debonding process itself and find parameters for fast and smooth debonding of veneers, and the mechanical properties of the teeth and ceramics will be further evaluated. This should lead to a basic understanding of acoustic wave behavior in the materials and path the way for another, purely optical debonding method.

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