

Enamel thickness measurement with a high frequency ultrasonic transducer-based hand-held probe for potential application in the dental veneer placing procedure

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This study presents a novel approach to measure the enamel thickness potentially applicable to the veneer placing procedure. All experiments have been carried out on the extracted human teeth, using a high frequency ultrasonic transducer (50 MHz, Sonix, Springfield, VA, USA). The enamel thickness measurement results obtained with high positional accuracy by a scanning acoustic microscope (Tessonics AM1103, Windsor, ON, Canada) were compared with the measurements conducted in a hand-held mode by using the same transducer placed in a custom fixture. Finally, to validate the ultrasonic measuring results, the samples were cut down the long axis to expose the cross-section. The enamel thickness was measured in several points along the selected part of the exposed cross-section by using an optical microscope (Stemi SV 11, Carl Zeiss AG, Jena, Germany). The values of the enamel thickness received by using the hand-held probe vs. the acoustic microscope were in close proximity (~10% difference) and were also satisfactory close to the enamel thickness results obtained from the direct cross-sectional measurements (~12% difference). The authors suggested a measuring procedure that allows avoiding errors related to the ultrasonic beam localization on the tooth surface. The high feasibility of the ultrasonic pulse-echo measurements in a hand-held mode was demonstrated.

Key words: acoustic microscopy, high frequency ultrasound, enamel thickness measurements

1. Introduction

Dental veneers are thin layers of plastic, composite or ceramic material bonded over a specially prepared tooth surface [1]. According to the common placing procedure, most veneers require a partial removal of the enamel layer from the front surface of the tooth before restoration (figure 1). For a healthy tooth, it is recommended to remove at least 0.6 mm of the enamel [2]. It is also suggested that the thickness of the adhesive cement, which is used to fix the veneer onto the ground surface of the tooth, should not exceed 50 μm . [3] (i.e., it does not affect the thickness of the enamel layer required to be removed before restoration).

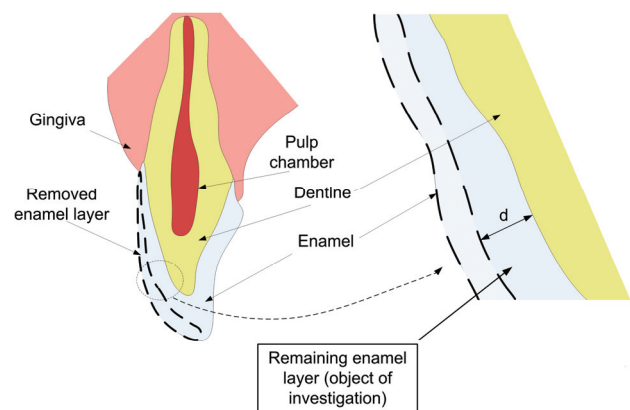


Fig. 1. Schematic diagram of an axial cross-section of a human incisor: dashed line shows the enamel layer to be removed during the veneer placing procedure. Right: close-up view of the enamel layer to be measured

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It is well established that bonding to the enamel layer is much better than to dentin regardless of dental adhesive systems, thickness of the cement layer and veneer laminates [1], [4], [5]. Therefore, it is extremely important to know the thickness of the enamel layer remaining after grinding to ensure the quality of restoration.

At this time, dentists do not have any non-invasive tools allowing the enamel layer measurements in a chosen spot [6]. Currently, dentists can score oral health using special indexes [7], [8] and statistically estimate the enamel thickness, but without any numerical values and certainty of the estimation. An appropriately selected ultrasound system in this case can help perform fast and reliable measurements without using unhealthy radiation, or complex and expensive equipment. In the recent publications related to the topic of ultrasonic enamel thickness measurements, the central frequency of the transducers used in evaluations were in the range from 10 to 35 MHz [6], [9]–[11], which resulted in limited time resolution and time delay accuracy.

The objective of this work was to investigate the potential of a high frequency ultrasonic transducer-based hand-held probe for thickness measurement of the enamel remaining after grinding of the tooth surface in the veneer placing procedure.

2. Materials and methods

In the conducted experiments, four tooth samples were randomly chosen from a set of extracted adult incisors. To avoid the influence of the environment on the experimental results, all specimens were kept in the same liquid (5% Thymol solution).

2.1. Instrumentation

A broadband, high frequency (HF), polyvinylidene fluoride (PVDF), focused transducer (50 MHz central frequency with 100% bandwidth, focal point distance equal 12 mm and half angular aperture $\sim 12^\circ$; Sonix, Springfield, VA, USA) was used for the measurements of the enamel thickness. The transducer was integrated into a specially designed hand-held probe with the purpose to simulate its potential usage in the dental office. Since a properly designed transducer tip is an essential part of the dental ultrasonic probe, in the performed experiments, we used a custom water-filled chamber. However, for practical purposes, the authors suggested a transducer tip design with a water inlet providing a laminar flow of water for coupling the transducers to the tooth surface (figure 2).

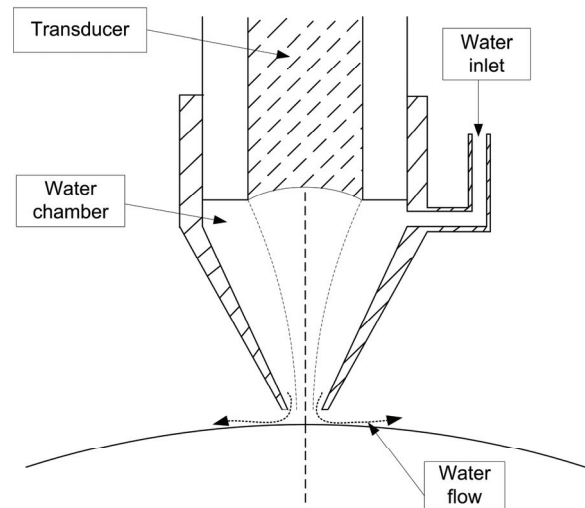


Fig. 2. Schematic representation of transducer–tip assembly that can be used for practical purposes

The same HF transducer was then installed into a scanning acoustic microscope (SAM) system (Tosonics AM1103[12], Windsor, ON, Canada) and used for validation of the enamel thickness measurements made by the hand-held probe. Additionally, an optical microscope (Stemi SV 11, Carl Zeiss AG, Jena, Germany) was used for direct measurements of the enamel layer thickness in the exposed by cutting cross-sectional areas of the tooth samples.

2.2. Thickness measuring procedure

The measuring procedure can be explained as follows. The thickness of the enamel layer d can be calculated from the known relationship: $d = \Delta t C / 2$ (where Δt is round-trip time and C is the speed of sound in enamel). The difficulty of using this equation for practical purposes is related to the measuring uncertainty of its components (more details about propagation of the ultrasonic beam through dental layers can be found in [13]).

The first parameter, the round-trip time, was determined by measuring the time delay Δt between the echoes from the surface of the sample and the target interface (figure 3).

The second necessary parameter is the sound velocity C , which depends mainly on the mechanical properties of the medium. It is known that the dental enamel is anisotropic[14]–[17] and its features depend on several factors (e.g., alignment of fiber-like apatite crystals, demineralization, the sample storage liquid, etc.). For this reason multiple papers [13], [18], [19] report different values of the velocity of sound in the dental enamel, which is usually assumed

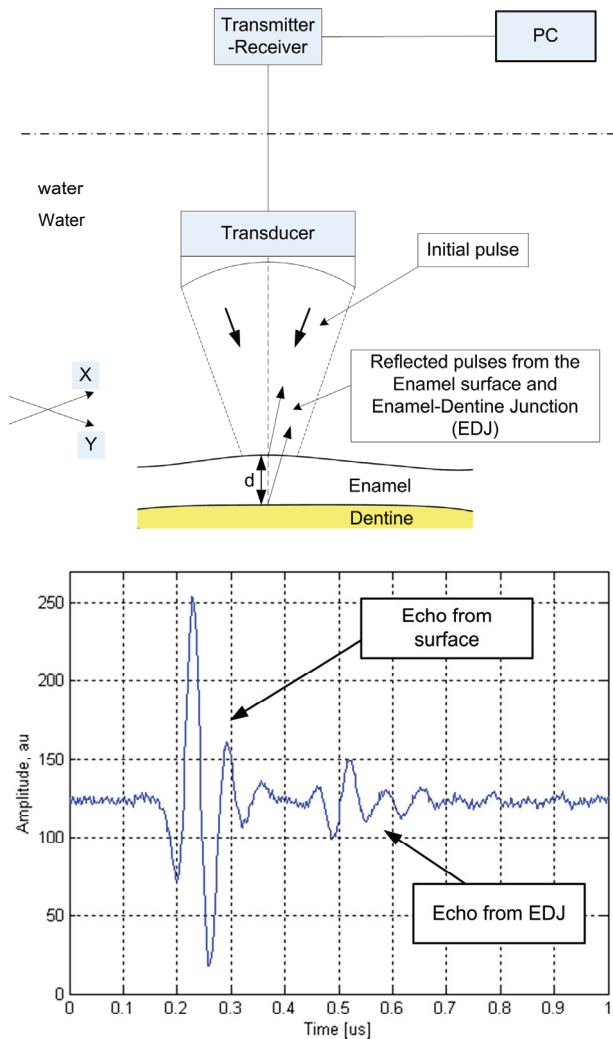


Fig. 3. Schematic diagram of the measuring setup, showing focused ultrasound beam path. Right: an example echo signal received from the enamel–denture structure (A-scan)

in the range of 5900 ± 300 [18]. The differences in the sound velocity values can be also due to the known fact that certain alignment corrections are necessary before the probe is positioned perpendicular to the surface to get an appropriate waveform with recognizable echo signal from the enamel–denture junction [20]. In the current investigation, the velocity of sound was measured by using the following approach. At first, one of the tooth samples was cut down the long axis of the tooth to expose the cross-sectional area, allowing direct measurement of the enamel thickness with the optical microscope. Then the same cross-sectional area of the tooth sample was analyzed using the SAM (A-scan, figure 3) and the round-trip time was determined. It is important to note that the suitable waveform was selected by carefully adjusting the position of the sample, and the results were recorded only if the operator deemed the

wave to be satisfactory. Knowing the distance (i.e., the enamel layer thickness) and the round-trip time it was possible to estimate the velocity of sound in the enamel to be 6100 m/s and this value was used in further calculations. The properties of the enamel were assumed to be homogeneous and isotropic, therefore, a constant value of the velocity of sound was used in the calculations. This approach allowed us to consider the time of flight and a proper localization of the ultrasonic beam path as the main uncertainties influencing the accuracy of the further measurements.

2.3. Nondestructive measurements of the enamel thickness

The measurements were divided in two groups; one group of measurements was done using the SAM system, while the second one was carried out with a hand-held probe. In both cases, special markers were to localize the position of the ultrasonic beam on the surface of the tooth samples. Two notches (along and across the tooth) were made on the surface of each tooth by means of a special linear saw (Wire Saw WS-22, K.D. Unipress, Poland). The notches were 0.15 mm wide, enough for being clearly noticeable on the surface of each sample (figure 4).

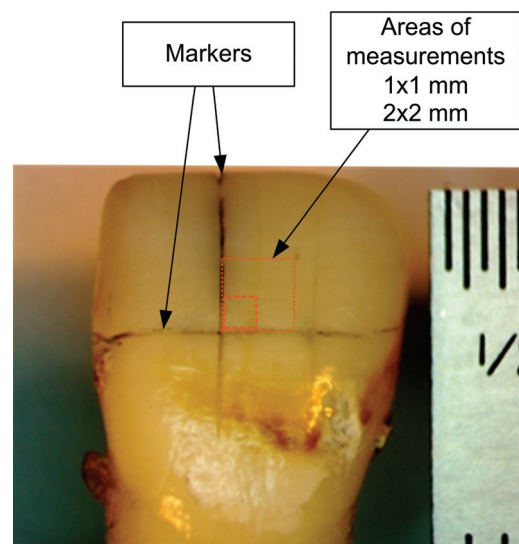


Fig. 4. An example of the marked tooth surface (visible scale on the right is 0.5 mm)

Rectangular areas of $1 \text{ mm} \times 1 \text{ mm}$ and $2 \text{ mm} \times 2 \text{ mm}$ were singled out on the surfaces of each sample (figure 4) and then examined using the SAM. The time of flight was obtained from the A-scans recorded at 10 randomly chosen points within each area.

To study the ability of the hand-held probe to measure the thickness of the remaining after grinding enamel layer, three samples of the available teeth were specially prepared by a dentist (the intention was to remove the thin enamel layer, in accordance with the veneer placing procedure [21]). The same grinding tools as in the dental veneer placing procedure were used for that purpose. The measurements were taken before and after grinding the samples. The observer was trying to position the probe tip for each of the measurements in the center of the $2\text{ mm} \times 2\text{ mm}$ area shown in figure 4. The obtained thickness measurements are presented in figure 5.

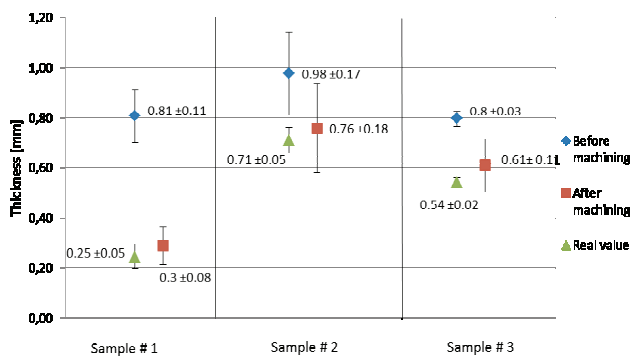


Fig. 5. Average values of the enamel layer thickness measurements, before and after the grinding process (the velocity of sound used in the calculations is equal to 6100 m/s)

To check the “sensitivity” of the ultrasonic measurements to the enamel grinding, a separate tooth sample was prepared as follows. At first, the sample was cut down the vertical notch and the thickness of the initial enamel layer was measured under the optical microscope. Next, the enamel thickness was determined in a chosen spot of the $2 \times 2\text{ mm}$ area by using both the SAM system and hand-held probe. After each consecutive grinding of the tooth sample, the measurement process was repeated. The results of all conducted measurements are shown in figure 6.

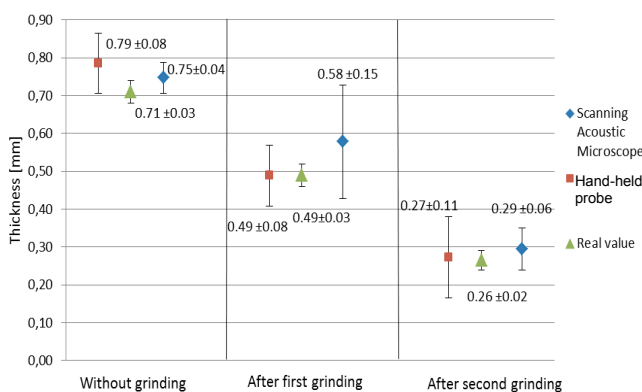


Fig. 6. The enamel thickness values: initial and after the first and the second grindings of the tooth surface

3. Results

The average and standard deviation (SD) of the enamel thickness in each of the measuring areas (i.e. $1 \times 1\text{ mm}$ and $2 \times 2\text{ mm}$) were calculated (the table). There was no significant difference between the results received in each area (the variation of the uncertainty value depends on the natural fluctuations of the enamel–dentin junction). Hence, the $2\text{ mm} \times 2\text{ mm}$ area was selected for further measurements.

Table. The average results of the enamel thickness measurements

# of the sample	Measuring area			
	1 mm × 1 mm		2 mm × 2 mm	
	thickness of the enamel (mm)	SD (%)	thickness of the enamel (mm)	SD (%)
1	0.79	4.06	0.8	3.84
2*	1.04	12.07	0.97	12.59
3	0.78	4.26	0.8	6.58

The bigger deviation can be explained if we assume that, in this particular example, the curvature of the enamel–dentin interface was much sharper than in other measuring areas of the tooth or much higher anisotropy occurred in this particular spot.

Average values of enamel thickness are shown in figure 5. For the sample # 1, the results show that it was prepared correctly since the dentist removed around 0.5 mm of the enamel material and the thickness of the remaining enamel layer was enough to “insulate” the veneer from the dentine. For the other two samples, less enamel material was removed than it was intended. To verify the results of ultrasonic measurements, after grinding, each of the three samples was cut down the long axis, so that the enamel layer could be measured under the optical microscope (“real values” shown in figure 5). The results obtained with the optical microscope have significantly lower uncertainties since the enamel thickness was measured directly along the edge of the cross-section exposing the enamel–dentin junction.

The enamel thickness values before and after grinding are shown in figure 6. It can be seen that the enamel thickness values received from the hand-held probe and the acoustic microscope are close. The average discrepancy was 5, 16 and 5%, respectively. The difference between the enamel thicknesses obtained with the optical microscope (real value) and the values measured by the hand-held probe was 10% or less. Taking into account the uncertainties, the results in both cases are practically independent of the level of grinding, hence supporting the possibility of using the ultrasound technique in this specific enamel measurement application.

4. Discussion

Ultrasonic measurement of the initial thickness of the enamel and its remaining thicknesses after consecutive grindings it was found to be easy to implement by applying the hand-held ultrasonic probe. Since the intensity of the echo signal depended on the probe tip angle relative to the enamel surface, the probe was always aligned perpendicular to the enamel surface by selecting the highest amplitude of the EDJ echo signals.

Reproducibility is an important aspect of any dental hand-held probe based diagnostic technique. Furthermore, in the ultrasonic measurement of the enamel layer thickness remaining after grinding, reproducibility will basically establish the axial resolution (minimal thickness change that can be measured) of the method. The calculated axial resolution of the used 50 MHz transducer-based hand-held ultrasonic probe was 0.12 mm in the enamel. This resolution should allow measurement of the enamel thickness in the veneer placing procedure with a relatively high degree of accuracy. However, to achieve this resolution in a dental diagnostic procedure, a few limiting factors have to be taken into account. First, it is difficult to repeatedly place the hand-held probe exactly in the same spot on the unmarked enamel surface of an “alive” tooth. Second, there is a gradual increase in the thickness of the enamel layer between the cervical and incisal margins of the tooth which can considerably distort the repeated measurements of the enamel thicknesses in case the probe is slightly displaced from the initial position. In addition, the manipulation of the probe to achieve a proper alignment relative to the enamel layer surface can result in slight displacement of the probe on the surface. To eliminate the mentioned above factors, limiting the axial resolution of the hand-held probe, the enamel thickness measurements can be done in specially selected spots formed on the enamel surface by means of calibrated drill bits.

The accuracy of the hand-held probe in measuring actual enamel thickness is highly dependent upon the longitudinal ultrasound velocity in enamel. This velocity shows some natural difference between teeth and also can depend on the age of the patient, probably due to changes in the density of the enamel. Another particular characteristic of the dental enamel is its anisotropy. Sound propagates through anisotropic enamel due to the specific arrangement of the hydroxyapatite crystalline rods. Such hydroxyapatite rods are found in rows along the tooth, and within

each row, the long axis of the enamel rod is generally perpendicular to the underlying dentin, which usually results in different values of ultrasound velocity for longitudinal and transversal enamel sections. So, the direct measurement of the sound velocity in enamel remains the current technique of choice. As was shown above (see subsection 2.2), in the present study, the longitudinal ultrasound velocity was calculated by determining the time delay between the echoes received from the surface of the sample and the enamel–dentin interface, and directly measuring the thickness of the enamel with the optical microscope. The average velocity of 6100 m/s is at a high end of the range reported in the previous publications [13], [18], [19]. This could be due to the fact that our measurements were all carried out essentially parallel to the rod direction and, therefore, a relatively high ultrasound velocity was to be expected.

The accuracy of the conducted measurements is also considerably dependent on the sharpness of the reflected signal (figure 3), which in its turn depends on the parameters of the used transducer, such as Q value, focal distance, etc. Thus, the focal distance (in our case 12 mm) should be adjusted to locate the focal spot in close proximity to the enamel–dentine interface. Another important component of the measurement accuracy is the technique by which the reference points defining the time delay between the reflected signals were determined. A special signal processing algorithm was developed for this purpose.

5. Conclusion

Potential applicability of the high frequency ultrasonic transducer-based hand-held probe to measure the enamel thickness in the veneer installation procedure was demonstrated. The HF ultrasonic probe equipped with a specially designed water chamber tip allowed measuring the enamel thickness of the extracted human front teeth with an accuracy of around 10%. The first part of the experimental work has shown that the developed hand-held probe can be effectively used for the enamel thickness measurements before and after the grinding process completion. The second part of the conducted experiments has demonstrated that the developed hand-held probe effectiveness in detecting the enamel thickness changes after three consequent grindings. The enamel thickness measurement results obtained with the hand-held probe encourage further work in this field.

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