Laser Ultrasonic Technique for Evaluating Human Dental Enamel

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Abstract. A non-destructive laser ultrasonic surface acoustic wave technique has been demonstrated to quantitatively evaluate the elastic response of human dental enamel. We demonstrate the system performance by measuring surface acoustic wave velocity in sound and demineralised enamel. In addition, progressive measurements were made to monitor the change in the enamel elasticity during a two week remineralisation process. The results are presented and they confirm the efficacy, as well as illuminating the progress, of the treatment.

1. Introduction

Dental caries, one of the most common diseases, is caused by the excessive mineral dissolution of tooth enamel [1]. The level of enamel mineralisation, which correlates closely to its elastic response [2-4], is hence an indicator for the healthiness of the tooth. However, conventional diagnostic methods, such as tactile and X-ray [5], are relatively ineffective for providing quantitative assessments. In this regard, a non-contact and non-destructive technique for localised quantitative evaluation of the elastic response of human dental enamel is desirable.

A surface acoustic wave (SAW) is a type of elastic ultrasound which propagates across the material surface with a wavelength dependent probing depth [6]. Its propagation velocity is directly related to the elastic constants of all the material layers it probes [7]. Determining the SAW velocity of different frequency components (different penetration depths) gives a dispersion spectrum whose slope and curvature reveal information about the elastic and geometric parameters of the specimen [8-10].

In this paper we present a validated laser SAW method [11] and its novel application of quantitative evaluation of the elastic response of human dental enamel. The measurement technique is briefly discussed. The elastic properties of human enamel are then considered and the measurement results of sound and demineralised enamel, as well as progressively remineralised enamel, are presented and discussed.
2. Laser Ultrasonic Technique

Detailed discussion and extensive validation testing results of this laser ultrasonic SAW dispersion technique can be found in a previous publication [11]. Key details only are presented here. The schematic of the measurement system is illustrated in figure 1.

A quadrupled Nd:YAG laser operating at 266 nm (~5 ns pulse duration) was used to excite surface waves on the samples. The source was focused into a thin line by a cylindrical lens onto the sample surface, as shown on the right of figure 1. The absorbed laser energy produces localised heating and causes rapid thermo-elastic expansion around the illuminated region, hence generating ultrasound [12, 13]. In this setup, test samples were placed on a manual Z-stage such that the irradiated line-source width can be tuned sufficiently narrow to generate broadband SAW, which is desirable for dispersion measurement. In the current study, the bandwidth of the generated SAW typically spanned from 1 ~ 25 MHz [14]. During measurements the laser pulse energy and the sample surface were constantly monitored to ensure non-destructive operation.

The SAW impulse was detected by an Optical Fibre Interferometer (OFI). The OFI consisted of a 1550 nm continuous-wave laser source, a 3-port optical fibre circulator and a photo-receiver. The OFI operation is similar to a reference beam interferometer [11]. The coherent laser light from the source was coupled into the circulator. As the light arrives at the end of the cleaved middle port (the sensing tip), it is split into the reference and the measurement beams by internal reflection and external reflection, respectively. The path difference of the two beams, and hence their relative phase, depends only on the separation between fibre tip and sample surface. In a typical ultrasonic measurement the surface wave modulates the measurement beam path-length and the interference pattern becomes a good measure of the absolute acoustic waveform. The sensing port of the circulator was placed on a micron-precision three axis (XYZ) positioning-stage to adjust the measurement position. All measurements were made with a probe-to-sample separation of 5 mm or smaller and between 1 mm and 12 mm from the line-source.

The propagation velocity of the SAW, \( c_R \), is governed by the elastic properties of the material layers within the frequency dependent penetration depth. The SAW penetration depth, \( z \), can be estimated from the relation [7, 15]:

\[
    z \approx c_R / f ,
\]
where \( f \) is the SAW frequency. As a broadband SAW propagates through a material surface, the higher frequency components have shallow penetration depth and are more influenced by the elastic parameters of the surface layer. On the other hand, the lower frequency components penetrate deeper and are influenced more by the bulk elastic parameters. Typically \( c_R \) is proportional to the elastic modulus but inversely proportional to the density [7]. In an isotropic homogeneous medium \( c_R \) is independent of the penetration depth (having a constant value for all frequency components) as well as propagation direction. In a complex inhomogeneous medium \( c_R \) becomes a function of signal frequency and the SAW is dispersed [15]. The characteristics of the dispersion curves depend on the nature of the specimen.

The experimental frequency dependent \( c_R \) and hence the dispersion curve was determined from two of the measured SAW signals, at locations \( x_1 \) and \( x_2 \), using the following equation [11]:

\[
c_R(f) = 2\pi f \frac{x_2 - x_1}{\phi(f)},
\]

where \( f \) is the SAW frequency and \( \phi(f) \) is the phase difference between the two signals derived from their Fourier spectra.

3. Evaluation of Human Dental Enamel

Kushibiki et al. [16] used line-focused-beam scanning acoustic microscopy and measured the SAW velocity as a function of propagation direction on extracted human incisors and reported that the velocity value varied between 3105 m.s\(^{-1}\) to 3155 m.s\(^{-1}\). Peck and colleagues [17] repeated the investigation on the surface of human permanent molars and reported that the SAW velocity varied between 3075 m.s\(^{-1}\) to 3142 m.s\(^{-1}\).

A recently extracted sound human incisor was selected for this initial study because this type of tooth has a large flat area of enamel on its front surface. In addition, the enamel thickness is relatively constant (~1 mm) over a wide region near the centre of the incisor front surface. This is desirable because the measured SAW dispersion will not depend significantly on the uneven thickness of the enamel layer but rather on the elasticity variation.

Artificial WSL, which is similar to a natural WSL and widely used for dental research [18], was created on the sample. About ~70% of the front surface of the incisor was first abraded and polished and a window of about 3 mm by 3 mm was left exposed while the rest of the tooth was coated and protected with nail varnish. The sample was then placed in demineralisation solution (pH = 4.5) [19] for five days. After the treatment, the nail varnish was removed. The WSL enamel is low in mineral (10 ~ 70% of the value for sound enamel) and thus has lower elastic modulus and consequently lower SAW velocity. A WSL layer developed on top of sound enamel is similar to the two-layer system and dispersion is expected.

The healthy region of the sample was first measured, as depicted in figure 2(a). The line-source (illustrated as the line) was irradiated near the edge of the enamel surface and the SAW propagated in the direction horizontal to the tooth axis. The recording of the surface waves was made at several positions along the propagation path (illustrated as the dots). The measurement was repeated ten times.

![Figure 2](image-url) Illustrations showing the positions of the SAW generation and detection on (a) the healthy region and (b) the WSL region of the tooth sample.
For the measurements on the WSL region, as illustrated in figure 2(b), we irradiated the line-source near the top edge of the tooth and allowed propagation across the lesion in the direction parallel to the tooth axis. Surface waves were recorded at various locations especially near the junctions of the sound enamel and the WSL (illustrated by the dots). Again ten measurements were repeated. Dispersion spectra of sound enamel and WSL measurements were calculated and the ten-times-averaged values were used as the final results and are presented in figure 3 with standard deviation error-bars. It is important to note here that we only investigate frequency components between 7 ~ 25 MHz, corresponding to a penetration depth of 0.5 ~ 0.1 mm (using Eq. 1 and \( c_R = 3100 \text{ m.s}^{-1} \)). Frequency components of 1 ~ 7 MHz have deep penetration depth and were significantly influenced by the underlying dentin is not important for this study.

In the sound enamel the SAW propagates as in a relatively homogeneous single layer system with \(~3150 \text{ m.s}^{-1}\). This value compares well with previously reported values [16, 17]. In the WSL region, the influence of the lower elastic lesion layer results in a slower initial SAW velocity value which continues to drop as the influence of the lesion layer became more dominant for higher frequency components. This dispersion profile fits well with expectation and the differences between the two dispersion spectra are significant (about 10 % drop in velocity value).

Having demonstrated the ability of the laser ultrasonic technique in evaluating and differentiating sound and WSL enamels, we extended the study to measure the progressive elasticity variation of artificially demineralised human enamel during remineralisation treatment. The same incisor sample was again used in this study. It was soaked entirely in the remineralisation solution (pH = 7.0) [20] for two weeks, the solution being renewed after the first week. Four sets of ten measurements were taken during the two week period after 4, 7, 10 and 14 days of treatment. The measurement procedure and the measurement regions were identical as before.

The final averaged dispersion curves (ten measurements for each set) of the sound enamel and the WSL measurements after 4, 7, 10 and 14 days of remineralisation are shown in figures 4 and 5, respectively (with different vertical scales). All of the results have less than 3 % standard deviation and the error-bars are not shown for the clarity of the figures.

For the sound enamel the SAW velocities are almost unchanged at \(~3150 \text{ m.s}^{-1}\) (less than 1% variation) during the two weeks of remineralisation treatment, which indicates that the treatment causes no change in the sound enamel. On the other hand, significant changes can be observed in the
WSL results with a trend towards increasing velocity values in the dispersion curves as the number of days of remineralisation increases. This observation suggests that the elastic modulus of the lesion layer has increased in value during the first 7 days of remineralisation. In the second week of the treatment, the increase in SAW velocity is minimal, which could be explained by a saturation of the remineralisation process.

![Figure 4](image1.png)

**Figure 4.** Comparison diagram of the sound enamel results during the two weeks remineralisation treatment.

![Figure 5](image2.png)

**Figure 5.** Comparison diagram of the WSL results from the two weeks remineralisation treatment.

From these results it is clear that we have successfully evaluated the change in the SAW dispersion curves, which directly correlate to the elastic properties, of a human tooth under remineralisation treatment.

**4. Conclusion**

In this paper we presented a laser ultrasonic technique and applied it to evaluate the elastic response of extracted human dental enamel. In sound enamel, the measured SAW velocity matched well with previously reported values. In the artificial lesioned region, the SAW velocity value was significantly lower and displayed significant dispersion. We have also presented the results of progressive
monitoring of a remineralisation process and shown that the SAW velocity increases in the lesion region only.

Although in-vivo tests have not yet been performed, the laser ultrasonic technique is a good candidate as a new examination tool for dental research purposes. Contrasted with the conventional destructive nano-indentation method and the limited discrimination provided by X-ray procedures, laser ultrasound provides repeatable non-destructive evaluation which can be used to study lesions of different severity and depth as well as verify the efficacy of different remineralisation methods.

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