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Evaluation of Ultrasonic Direct Contact, Immersion, and Layer Resonance Methods for Assessment of Enamel Thickness in Teeth

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Abstract

Wear of dental enamel is a growing problem, but is clinically difficult to diagnose and monitor. An accurate and easy to use non-destructive method for the measurement of enamel thickness would be useful for early diagnosis of enamel loss and for monitoring progression. Ultrasound has been identified by several researchers as a potential tool suitable for enamel thickness measurement. However, in-vitro studies have shown that whilst the method is feasible it suffers from wide variability. The methods proposed to date rely on the measurement of the time of flight of an ultrasonic pulse through the enamel layer. This requires the operator to locate the enamel dentine junction. In this work three methods are evaluated to try to reduce this variability and investigate some practicalities of the approach. Time of flight methods using both contact and immersion transducers were used. Immersion transducers gave the most accurate results, within 10 to 15% of values deduced from tooth sections, but would be harder to arrange for in-vitro measurements. Preliminary studies have also shown that it is possible to achieve a resonance in the enamel layer and measure thickness that way. Whilst this approach needs further experimental refinement it has the potential to be used for much thinner enamel layer thicknesses.

Introduction

The enamel which makes up the outer layer of teeth (see Figure 1) is hard and wear resistant and so the rate of enamel loss through wear under normal circumstances is low. However, life expectancies are increasing and teeth are therefore required to last longer. This means that assessment of tooth wear is becoming an important issue. Estimates suggested that 97% of a study group were affected by tooth wear and 7% showed pathological tooth wear needing treatment [1].

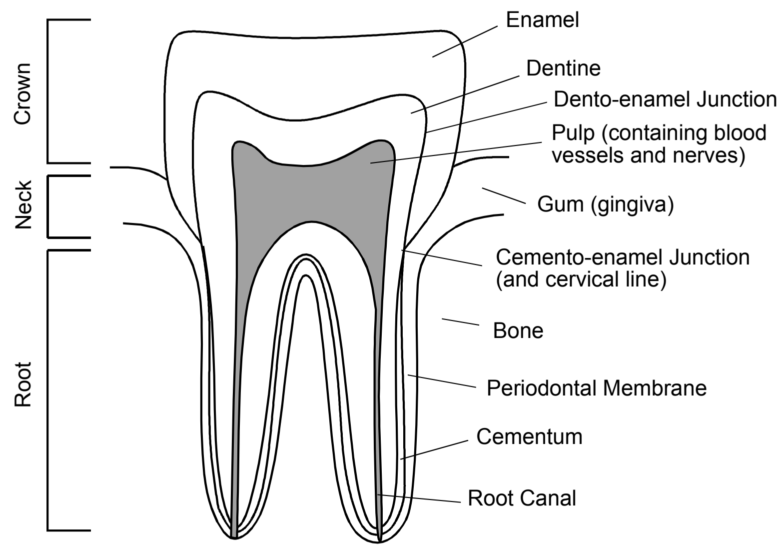


Figure 1. Schematic diagram of the internal struture of a human tooth.

Teeth enamel can wear by a number of different mechanisms, which have been outlined in detail by Lewis & Dwyer-Joyce [2]. The most significant of these arises due to inter-tooth contact during thegosis or bruxism and mastication, where dietary particles trapped between the surfaces also influence the wear. Tooth wear mechanisms are accelerated with an acidic oral environment and as people are developing a greater taste for sweet and acidic foods and drinks this will have an impact on tooth wear.

Young children are particularly at risk. For example a study of 14 year olds showed in some cases they had an enamel loss rate of 0.1 – 0.15 mm/year [3]. There is a greater emphasis in dentistry now on early diagnosis of dental disorders and prevention. *In-vivo* tools to assist dentists in detecting problems are therefore extremely helpful and will help improve these processes.

A number of studies have used direct measurements of sectioned extracted human teeth to determine enamel thickness [4,5,6]. Clearly this is the easiest way to take the measurements it will provide the most accurate data. However, extracted teeth are very rarely sound and will not give a good representation of how wear is progressing on live intact teeth.

Dental clinicians tend to use indices for classifying tooth wear, based on an evaluation of changes in the form of the occlusal surface. This can be combined with estimations of the degree of worn enamel and the amount of exposed dentine [7] to provide guidance for the need for treatment [8]. Research trials have also quantified in-vitro enamel wear by recording changes to tooth impressions using stereomicroscopy [9] or coordinate-measuring devices [10,11].

Lees & Barber [12] established the feasibility of determining enamel thickness and tooth structure using acoustic echoes on extracted bovine teeth. The acoustic coupling, however, was achieved by grinding a flat on the tooth. The most successful studies of tooth structure and have been performed on extracted teeth immersed in a water bath as an ultrasonic couplant. Kossoff & Sharpe [13] investigated the internal structure of the tooth and the presence of tissue in the pulp chamber. Ghorayeb & Valle [14] detected the location of amalgam restorations, cavities, and decay with ultrasonic scans. Culjat et al. [15] scanned around the circumference of a tooth mounted in a water bath to study the variation in enamel thickness.

For the development of a clinical device it is necessary to develop a probe that can be used with direct coupling acoustic to the tooth. A study by Huysmans & Thijssen [16] used a conventional ultrasonic thickness gauge with a conical Perspex delay line bonded to the transducer. The delay line was coupled with glycerol directly to the tooth surface. They took point measurements of enamel thickness on an extracted human tooth. Enamel thicknesses in the range 0.5 to 1 mm were measured at various sites and by different operators. Further work [17] has explored the repeatability of such measurements and concluded that changes in enamel thickness of less than 0.33 mm could not be reliably measured.

The aim of this work was to evaluate three different non-destructive ultrasonic techniques for measuring tooth enamel thickness to allow quantitative determination of tooth wear. The main emphasis was placed on assessing accuracy of the methods and whether they can be practically developed into a tool for taking *in-vivo* measurements. Such a device would help dentists in early detection of a wear problem and treatment planning as well as addressing the general lack of enamel thickness data available identified by Harris [18], which would be useful in providing a norm against which samples with genetic, chromosomal or other abnormalities affecting denture or enamel formation can be compared quantitatively.

Response Of A Tooth Enamel Layer To Ultrasound

Reflection at a Layered System

Figure 2 schematically shows an ultrasonic pulse travelling through a water medium and striking a tooth. Reflection occurs at the water enamel interface, enamel dentine junction (EDJ) and any subsequent interfaces. There will also be reverberations within the layers. The proportion of the wave reflected back at an interface (known as the known as the reflection coefficient, R) depends on the mismatch in acoustic impedance of the materials either side according to:

$$R = \frac{z_2 - z_1}{z_2 + z_1} \tag{1}$$

where z is the acoustic impedance (the product of the density of the material and the wave velocity through the material) and the subscripts 1 and 2 stand for the material either side of the interface. If the waves are acoustically similar then most of the wave will pass through and R tends to zero whilst if they are very different then R tends to unity.

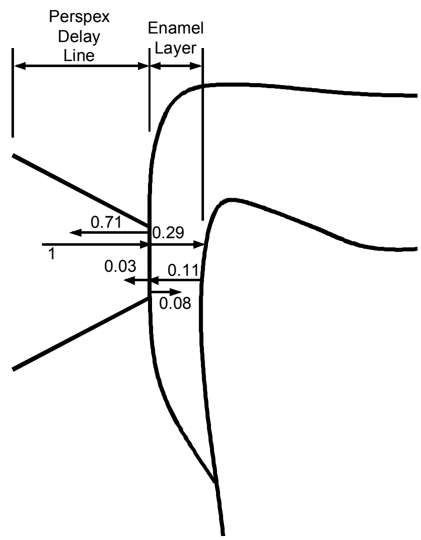


Figure 2. Schematic diagram of ultrasonic reflections from a tooth with a transducer coupled using a perspex delay line.

Table 1 gives some acoustic properties for the materials used in this study. It should be noted that a range of values for the wave speed in enamel and dentine have been quoted [13, 16, 19, 20] ranging from 4500 to 6500 m/s for enamel and 3800 to 4050 m/s for dentine. It is not clear whether the variability is inherent in tooth samples or caused by different testing approaches. In this study no independent measurement of wave speed has been attempted and the comprehensive data from [19] has been used.

Material	Density (kg/m^3)	Wave speed (m/s)	Acoustic Impedance (10^6 $kgm^{-1}s^{-1}$)
Perspex	1179	2730	3.2
Water	1000	1480	1.5
Enamel	2950	6500	19.2
Dentine	2150	4050	8.7

Table l. Acoustic properties of materials used in this study [19, 21].

The reflection coefficients for Perspex-enamel and enamel-dentine are 0.71 and 0.38 respectively. Using these two values the proportions of a wave of unit amplitude that are reflected and transmitted each time the wave strikes an interface can be determined. These ratios are shown on figure 2. The amplitude of the Perspex-enamel reflection (0.71) would thus be expected to be about twenty five times larger than the enamel-dentine reflection (0.03). In addition a phase change is expected as the wave is reflecting at a dense to less dense interface.

Time Domain Layer Thickness Determination

The time between the two pulses reflected from the enamel front and back face can be measured and, given the velocity of sound in the medium, the thickness of the layer can be deduced. Clearly, for this method to work it must be possible to spatially separate the incident pulse from the reflected pulse. Each reflected pulse has a finite size and in practice the two pulses must be separated by 3 to 4 wavelengths so that they do not overlap. The interval between the two pulses is $c/2f$ where c is the speed of sound in the layer and f is the ultrasonic frequency. The minimum measurable layer thickness is thus given by:

$$t_{\text{limit}} = \frac{3c}{2f} \tag{2}$$

This limit of the time of flight method is plotted as the upper curve on figure 3. Most work [12, 16, 17] has been carried out using conventional thickness gauges that operate at frequencies up to 15 MHz, thus limiting enamel thickness measurements to layers thicker than 0.5 mm.

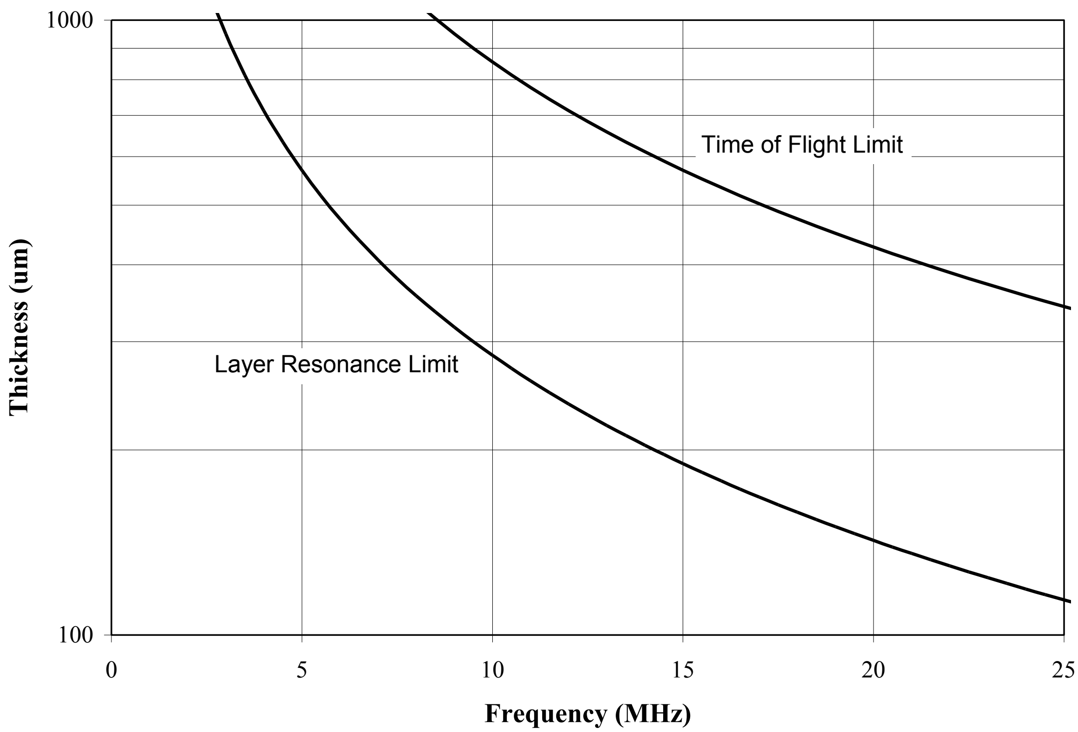


Figure 3. Limits for ultrasonic measurement of enamel thickness with test frequency (a) time of flight method, (b) layer resonance method.

Frequency Domain Layer Thickness Determination

If the enamel layer is thin then it is not possible to separate the front and back face reflected waves. Under these circumstances an alternative approach can be used. The whole of the collected signal (including components from the front and back face) is recorded and processed in the frequency domain.

This type of layered system has been studied by several authors [22, 23, 24] using a continuum model approach. Based on continuity of stress and strain at each boundary in the multi-layered system, these models can be used to predict the reflection and transmission of plane ultrasonic waves through a given system.

Figure 4 shows a continuum model prediction of the reflection coefficient spectrum for the layered arrangement of figure 2 for three different enamel thickness. The material properties used in this calculation are shown in Table 1. This is essentially the *impulse response function* of the system, i.e. it gives the response of the system for an incident wave of unit amplitude.

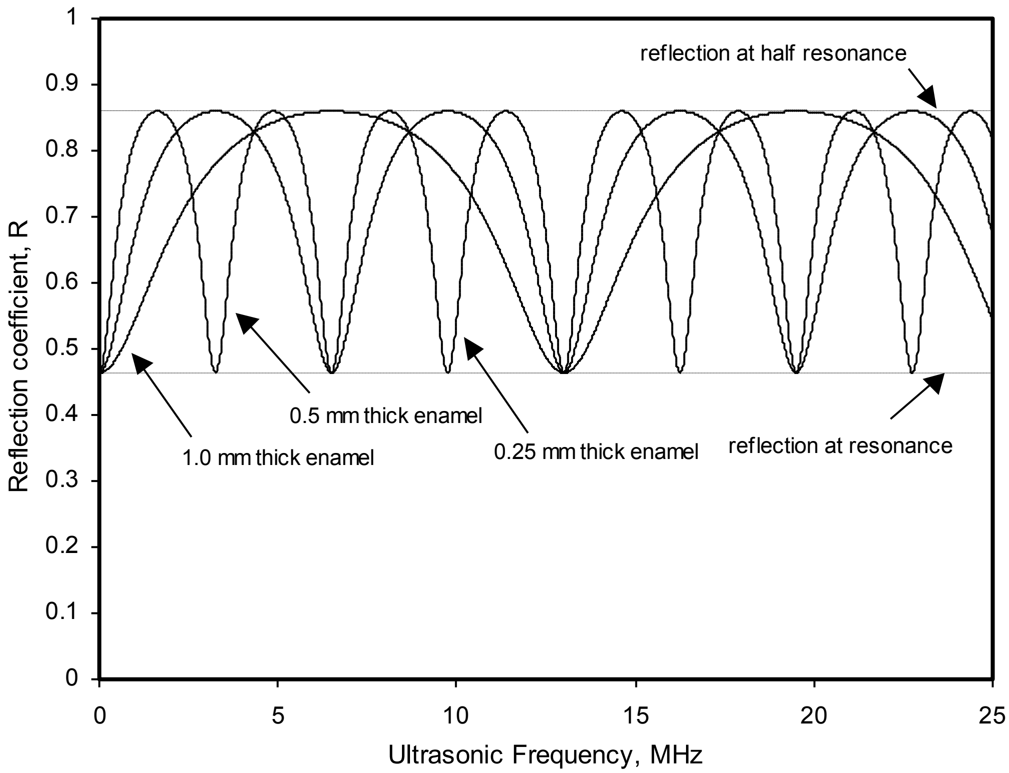


Figure 4. Continuum model predictions of the reflection coefficient spectrum from a layer of enamel between Perspex and dentine elements for three values of the enamel layer thickness.

Figure 4 shows a series of minima in the reflection coefficient spectrum for each layer thickness. These are the frequencies at which the enamel layer resonates. The resonant frequencies of the embedded layer are related to its thickness, *t*, and acoustic properties by [24]:

$$t = \frac{cm}{2f_m} \tag{3}$$

where, c is the speed of sound in the lubricant layer, m is the mode number of the resonant frequency and f_m is the resonant frequency of the m^{th} mode. The value of the reflection coefficient at resonance and at the half-resonance frequencies are given by [24]:

$$R_{res} = \frac{z_2 - z_1}{z_2 + z_1} \quad \& \quad R_{half} = \frac{z_1 z_2 - z_0^2}{z_1 z_2 + z_0^2} \tag{4}$$

It can be seen from consideration of equation (3) that higher resonant frequencies correspond to thinner layers. The minimum layer thickness that can be measured using this approach, given by equation (3), is plotted as the lower curve on figure 3. It is measurement of these resonant frequencies that can provide an alternative way of determining the enamel thickness down to layers of around one half to one third that measurable by time of flight methods.

Apparatus

Figure 5 shows a schematic of the equipment used for sending, receiving and processing ultrasonic pulses. The ultrasonic pulse receiver (UPR) generates short duration voltage pulses of amplitude 100 V and pulse width 0.15μs. The voltage pulses excite the piezo-electric element in the transducer that generates an incident ultrasonic wave. The wave transmits into the specimen and is partially reflected (according to equation 1) at any interfaces. The reflected wave then deforms the element in the same transducer (i.e. pulse echo mode) and generates a voltage signal. This signal is amplified by the pulser receiver unit, passed to an oscilloscope where it is viewed and digitised and then passed to the PC for further signal processing.

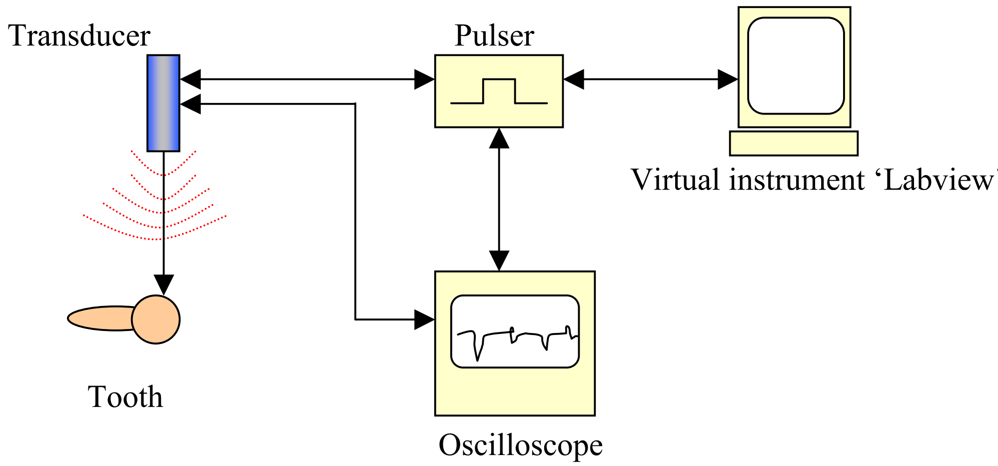


Figure 5. Schematic diagram of the instrumentation used for measurement of enamel thickness using an ultrasound.

Two types of transducer were used in this work. For the immersion measurements a 25 MHz spherical focussing transducer was used. The transducer had a focal length of 40 mm in water. For the contact measurements a planar type of nominal centre frequency 10MHz. A short conical Perspex delay line was bonded to the element. Internal reflections within the delay line can be superimposed on the reflected signal from an interface under investigation. The shape of the delay is therefore quite critical. Some experiments were performed to study the effect of the length and cone angle of the delay line; a length of 10 mm with an apex angle of 15° and a tip diameter of 2.4 mm was found to transmit and receive the clearest signal.

Signal Processing

For time of flight measurements of the full waveform was recorded and the distance between the peaks corresponding to the Perspex-enamel and enamel-dentine junctions were recorded. The enamel layer thickness is determined by using the speed of sound data of Table 1.

For the resonance based methods the first step is to acquire a reference signal. The transducer and delay line were removed from the tooth and a reflected pulse for the Perspex-air interface recorded. Since a Perspex-air interface causes almost complete reflection, this reflected wave is then equivalent to the incident wave. The reflections from the tooth were then recorded. These signals were passed through a digital fast Fourier transform (FFT). The FFT of the reflected signal is divided by that of the reference signal to give the reflection coefficient spectrum.

Results

Contact Transducer

Work was carried out on a single extracted human molar tooth. The transducer and delay line were held firmly against the tooth surface with a thin layer of water-based gel as a couplant (as shown in figure 6). After the ultrasonic measurements had been completed the tooth was carefully sectioned across the measurement plane to provide a visual assessment of enamel thicknesses.

Figure 6. Photograph of the transducer and delay line held against the specimen tooth embedded in resin.

The transducer was positioned at three test locations around the tooth periphery as shown in Figure 7. Also shown are micrographs of the sections through the tooth at the measurement locations shown. The arrows indicate the direction of wave incidence, the solid line the plane of the transducer front face, and the dotted line the extent of the enamel layer thickness at the measurement location.

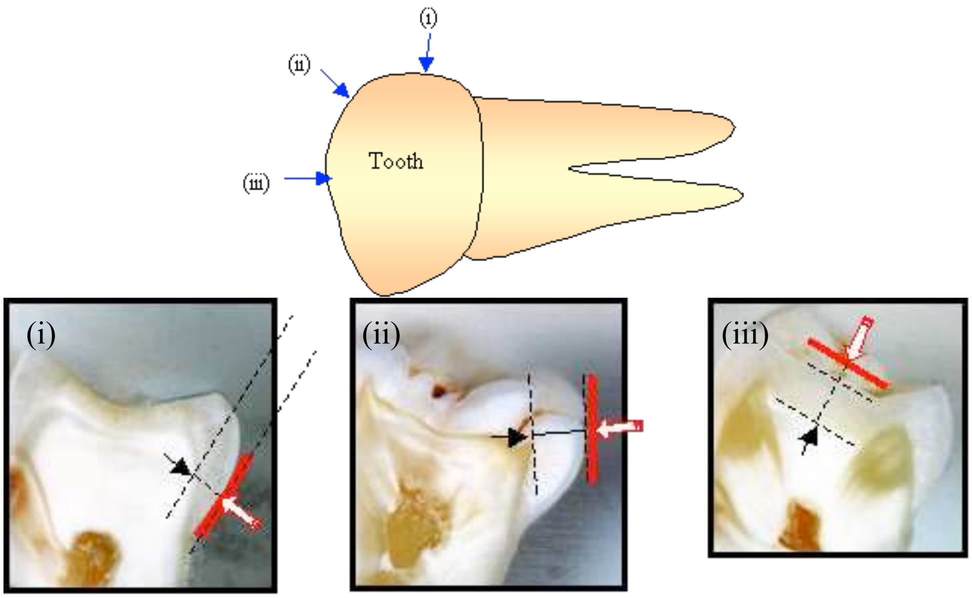
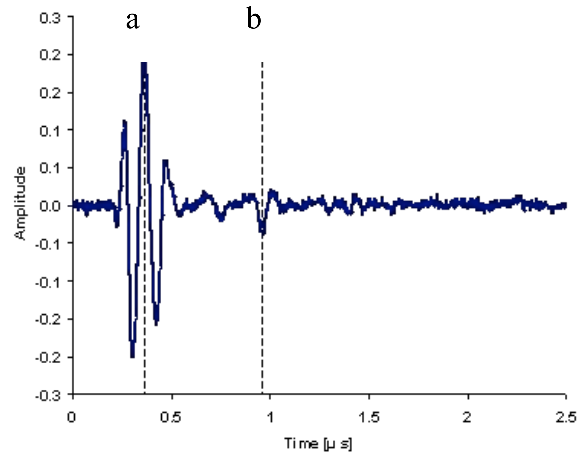


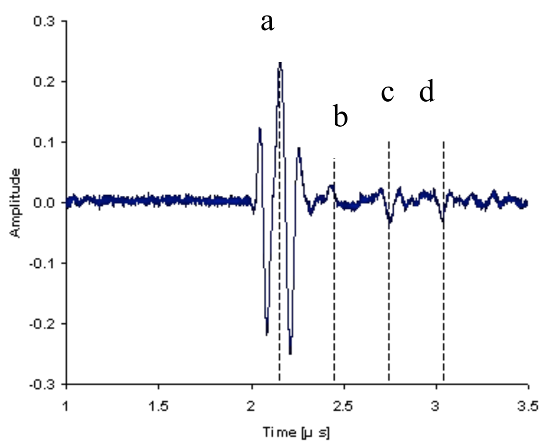
Figure 7. Tooth schematic indicating the three test locations (i) lower distal surface, (ii) upper distal surface, (iii) occlusal surface; and micrographs of the sections through the tooth recorded at the three locations.

Figure 8 shows the waveforms (ultrasonic A-scans) produced from each of the three transducer locations indicated. In the first two cases (i) and (ii) the first peak in the waveform, marked (a), corresponds to the reflection from the Perspex delay line to enamel interface. The second reflection, marked (b), corresponds to the enamel dentine junction. The enamel layer thickness is readily obtained from the speed of sound in the layer and the distance between these two peaks. When a wave reflects at a dense to a less dense medium there is a 180° phase change. This can be clearly seen in Figure 8(i) where the Perspex-enamel reflection is a peak whilst the enamel-dentine reflection is a trough. The time of flight is thus measured from the peak of (a) to the trough of (b) shown as dashed lines. In figure 8(ii) two further troughs (c) and (d) can be clearly seen, these are reverberations within the enamel layer. They are spaced at the same interval as (a) and (b).

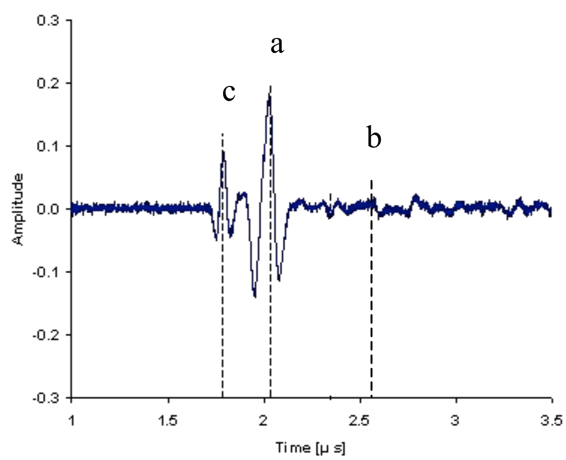
The reflected signal from the occlusal surface is slightly different as shown in Figure 8(iii). This is because the tooth surface at the crown is far from flat and a thick layer of gel had to be applied in order to couple the transducer to the enamel. The first reflection (c) is from the Perspex-gel interface. The enamel thickness is then obtained from the separation of the pulses (a) and (b).



(i)



(ii)



(iii)

Figure 8. Photographs of tooth sections at the three test locations (i), (ii), and (iii)

Table 2 shows time delay between the two reflections either side of the enamel layer for each of the three different transducer locations. If it is assumed that the speed of sound in enamel is

6500 m/s then the predictions for the enamel thicknesses can be calculated; this data is also shown in the table alongside the thickness determined from with microscopy measurements of the tooth after sectioning.

Site	(i)	(ii)	(iii)
Time delay, µs ± 0.02 µs	0.30	0.61	0.58
Calculated thickness, mm ± 0.15 mm	0.98	2.18	1.89
Measured thickness, mm ±0.1mm	1.3	1.9	1.7

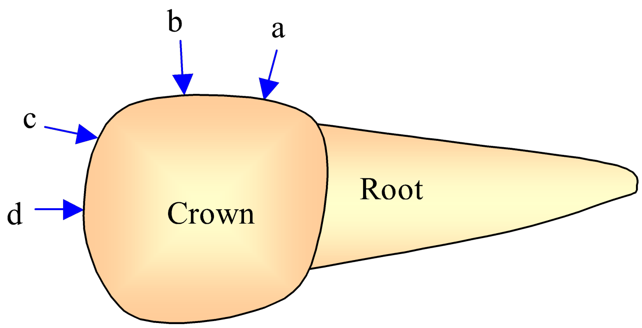
Table 2. Enamel thickness measurements of three locations around tooth periphery. Ultrasonic results are compared with optical measurements.

With the exception of site (i) the ultrasonic results are with 15% of the measured value. Given the difficulty in locating the EDJ reflection and also the uncertainty in the speed of sound in the enamel, this is a realistically indicative value for the accuracy of this approach. The error for site (i) is 25%. This site is at a region of rapidly changing enamel thickness. The delay line tip has a diameter of 2.4 mm. Effectively the ultrasonic results will be averaged over this area. Over this area there is a significant variation in enamel thickness and it is this that is thought to have caused the poorer accuracy at this location.

Immersion Transducer

To improve the spatial resolution of the measurements an immersion technique was used. The extracted tooth was immersed in water and the transducer positioned at the correct focal length and orientation using a gimble and lead screw arrangement. Figure 9 shows the transducer and positioning mechanism with the immersed tooth. Figure 10 shows the four measurement locations selected and a micrograph of the section of the tooth taken after testing.

Figure 9. Photograph of the transducer and positioning mechanism and the trasducer focusing on the immersed tooth.



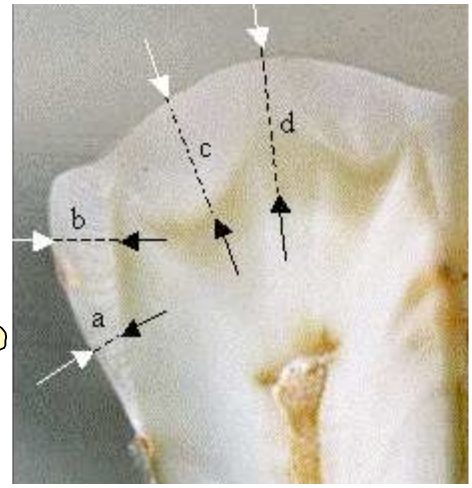


Figure 10. Measurement locations and micrograph of a cross section through the tooth indicating the measurement locations.

The spatial resolution of the transducer is greatly improved over the contact method described above. The spot size of a focused transducer is given by [25]:

$$d_f = \frac{1.028Fc}{fD} \tag{14}$$

where F is the transducer focal length, c is the speed of sound in the focusing medium, and D is the diameter of the piezo element. For the transducer used in these experiments at 25 MHz this corresponds to a spot size of approximately 300 μm. The reflection signal recorded at expected to be an average over this region. Table 2 gives the enamel thickness measured from the time delay between the enamel front and back reflections (as in the contact case above) and the value determined from the micrograph. The errors in the results are in the region of 10 to 20%.

Site	(a)	(b)	(c)	(d)
Time delay, μs ± 0.02 μs	0.20	0.40	0.70	1.00
Calculated thickness, mm ± 0.15 mm	0.65	1.30	2.30	3.25
Measured thickness, mm ± 0.1mm	0.7	0.9	2.2	2.6

Table 3. Enamel thickness measurements of three locations around tooth periphery. Ultrasonic results are compared with optical measurements.

Resonance Method

One tooth was embedded in resin and a flat was ground on the tooth side to generate an area of deliberately reduced enamel thickness. The 10 MHz contact transducer with delay line were used for this experiment. Initially a reflection was recorded from the end of the delay line without the tooth contact being made. Here the reflection is from a Perspex delay line to air interface, where R will be virtually one, hence the reflected signal is equal to the incident signal. This signal is passed through a fast Fourier transform (FFT) and is shown as the bold line on figure 11. This frequency spectrum shows that the centre frequency is actually closer to 8 MHz (rather than the expected 10 MHz) and the bandwidth around 5 MHz.

A signal was then recorded when the delay line was pressed against the tooth surface and coupled with a thin layer of gel. This reflected signal was also passed through an FFT. This reflected spectrum is also shown in figure 11. The reflection coefficient spectrum is obtained by dividing the signal reflected from the enamel layer by the reference signal. This is shown as figure 12. Figure 12 is the experimental analogue of the model results displayed as figure 4.

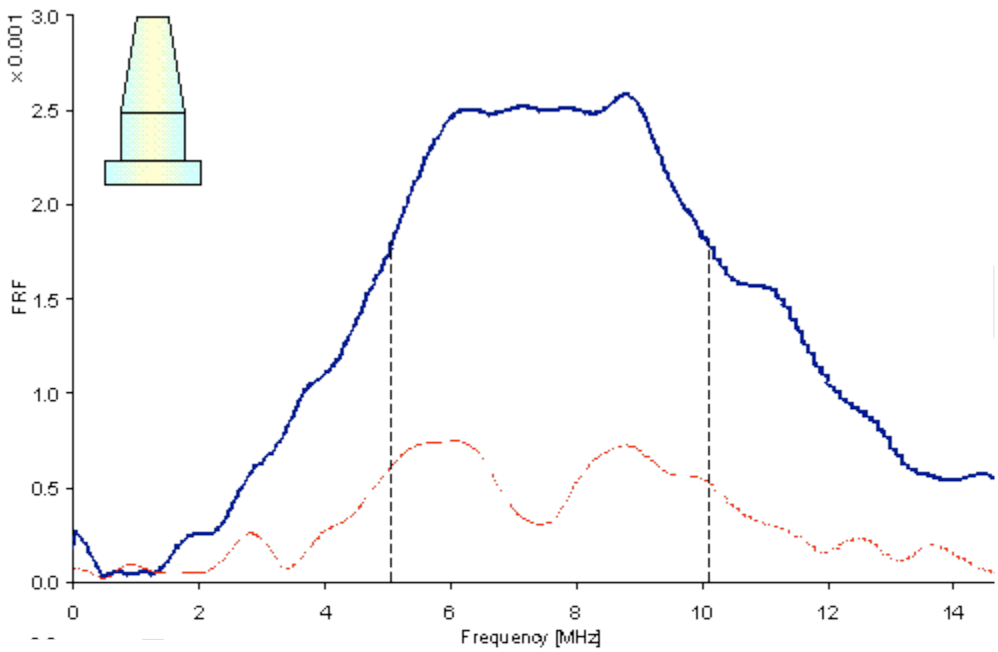


Figure 11. Frequency spectra of the refererence pulse (incident pulse) – bold line, and the pulse reflected from an enamel layer – faint line.

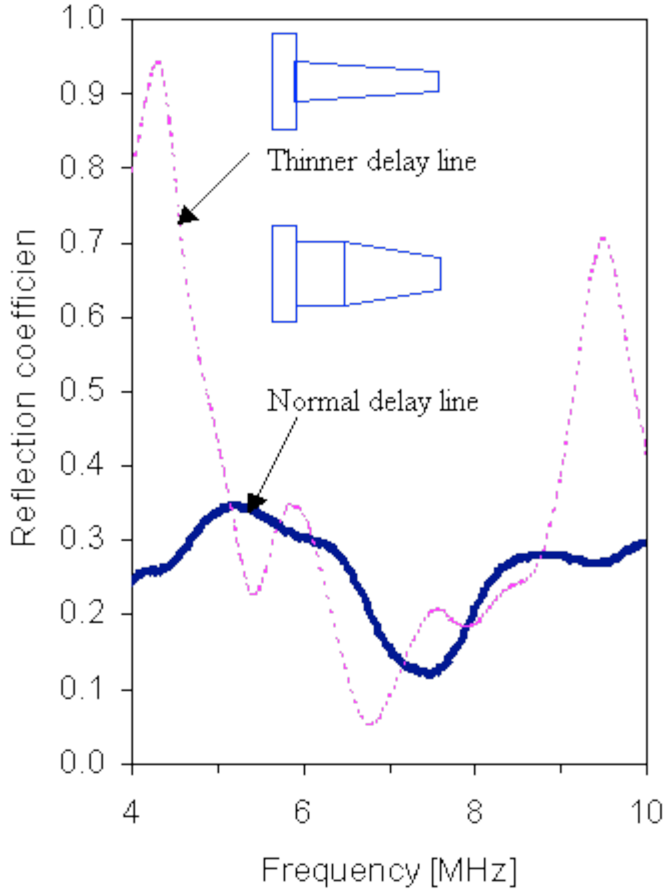


Figure 12. Frequency spectra of the refererence pulse (incident pulse) – bold line, and the pulse reflected from an enamel layer – faint line.

The experimental results do not show the same regular smoothly varying curves that might be expected from the theoretical model (figure 4). This is because the enamel layer is not a uniformly thickness parallel sided layer. However, both the reflected pulse (figure 11) and the reflection coefficient (figure 12) show a dip at a frequency of 7.5 MHz corresponding to the resonance frequency of the enamel layer. This gives (according to equation 3) an enamel layer thickness of 0.43 mm ± 0.10 µm. The applied measured enamel thickness at this location was measured as 0.52 mm.

Discussion

The measurement of enamel thickness by using the reflection of ultrasound is feasible in a laboratory environment. The acoustic impedance mismatch between enamel and dentine is such that a reflection at that interface is achievable. However, the geometry of the tooth surface and the EDJ is irregular and this makes the practical application difficult.

Firstly the sound wave must be coupled with the tooth surface. Water is an ideal couplant and the immersion method demonstrates good coupling. However, this is most easily conceived as an in-vitro method. It is common practice to use a water jet, rather than a full immersion tank, to inspect engineering structures, but in the human mouth this is likely to be difficult to achieve in practice. Therefore restriction to a solid delay line, for example Perspex, and a water based gel couplant is probably the most realistic solution.

Secondly the sound wave should strike the interface normally so that the reflection is received by the transducer. Figure 13 shows three signals recorded at different transducer orientations. When the transducer is approximately 10° off the normal the EDJ pulse is not visible (as shown in figures 13a and b). In practice the ultrasonic transducer has to be positioned carefully by hand until a satisfactory signal is observed (such as figure 13c). This requires some practice and familiarity with the equipment. For this to work in a clinical environment will require some training and possible the use of an oral stent or other transducer positioning system.

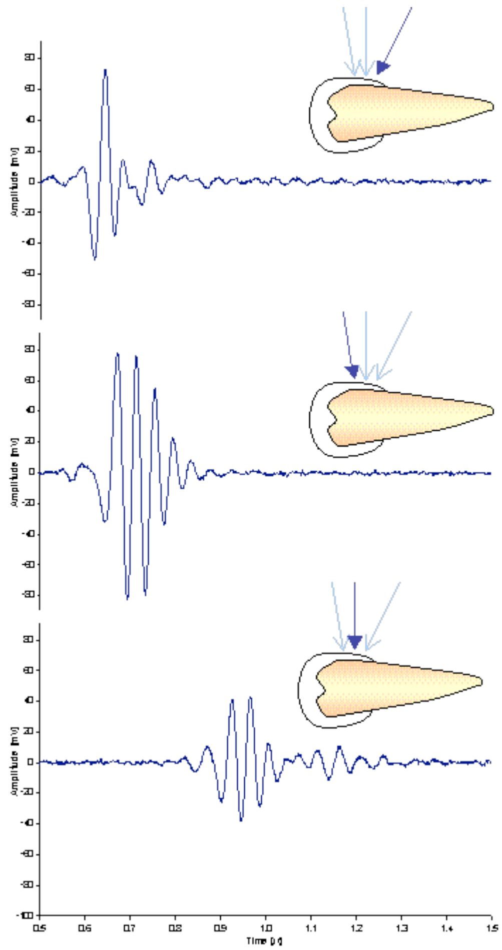


Figure 13. Pulses reflected back from the enamel surface and EDJ for three different transducer orientation angels. Only the third orientation successfully records the EDJ reflection.

A further issue is the uncertainty in the speed of sound in the enamel. This is a requirement for the thickness measurement. The literature [13, 16, 19, 20] has a range of values quoted and also apparent variations around the tooth profile as the enamel density changes. This will be a further source of inaccuracy that cannot be eliminated without some independent test method.

The enamel layer thickness varies around the tooth profile and in some regions a rapid transition is observed. The spatial resolution of an ultrasonic method is relatively low and for contact measurements is limited to the size of the delay line tip. Resolution is improved by means of high frequency focusing transducers operating under immersion; realistically this is limited to a laboratory method. Given the above limitations, at this stage it is suggested that measurements with a confidence of around 20% are achievable.

The detection of a frequency at which the enamel layer resonates indicates that it is possible to measure enamel layers by this method. This means that the minimum measurable layer can be extended down to 100 μm if a higher frequency transducer is used. Other layers may also resonate, for example the gel couplant, and under certain circumstances it may prove difficult to identify the required enamel resonance.

Conclusions

Three approaches have been explored for the measurement of enamel thickness in teeth using ultrasound; contact, immersion, and resonance. The first two approaches use a time of flight based method, whilst the latter records the frequency at which the enamel layer resonates.

It has been shown that all three methods can be used to determine the thickness and values in the range 0.43 to 3.25 mm were recorded. The accuracy is limited by the detectability of the required reflection, alignment of the transducers, and an uncertainty in the acoustic velocity in enamel.

A contact based method where the transducer is coupled to the tooth using a Perspex delay line and thin layer of water based couplant would be the easiest to use in-vitro. However, this has a lower spatial resolution and also has a lower limit of measurable layer thickness.

A resonance method has been shown for the first time to be a feasible alternative. This has the advantage that it can potentially be used to measure down to thicknesses of around 100 μm.

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