Immersing Teeth in Ultrasound

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Lead vests may soon no longer have a place in the dentist's office. New research shows that ultrasonic waves probably can be used in place of X-rays to detect various tooth anomalies. Ultrasound reveals tooth structure much like it reveals the sex of a baby in its mother's womb. As a result, a diagnostic ultrasound system (echodentography) is being developed that can be applied to teeth in order to detect cavities, decay and fractures, and even early stage abscesses. Ultrasonic waves are particularly sensitive to tight cracks and interface conditions between layers – dental features often difficult to interpret from X-ray images. Most importantly, due to its non-ionizing nature, ultrasound acquires a potential advantage over conventional X-ray imaging. When ultrasonic waves are used at low intensity levels, they do not cause any health risks. This article presents preliminary results of laboratory experiments conducted on extracted human second and third molars using a low-intensity, high-frequency setup. Three cases are examined: an intact (normal) tooth, a tooth containing an amalgam restoration, and a tooth containing a machine side-drilled hole in order to mimic a cavity at the enamel-dentin interface. One-dimensional *A*-scans and two-dimensional sector *B*-scans are obtained from a single ultrasound test. In addition, a measure of exposure to ultrasound, the spatial-peak temporal-average intensity, has been calculated and does meet the worst-case regulatory limit for exposure criteria for medical diagnostic ultrasound imposed by the Federal Drug Administration (FDA).

How Does It Work?

Acousto-ultrasonic image formation is in a way similar to optical image formation. It is even possible to record ultrasonic images directly on photographic film or store the images digitally on a computer for future processing. Like its optical counterpart, ultrasound uses reflective and refractive elements, such as lenses, prisms or mirrors, for beam formation and steering. Diffraction effects govern image resolution, and contrast factors in produced images depend on changes in absorption and/or impedance. When absorptive or impedance variations are insufficient to differentiate between features, phase contrast agents are available to compensate for any degradation.

A fundamental difference exists, however, between optical and ultrasonic techniques in that one cannot "see" acoustic waves directly. Ultrasonic images are obtained by waves propagating and interacting with the mechanical properties of tissue – a feature that makes this imaging modality complementary to existing diagnostic tools. Therefore a different means is required to provide a conversion of acoustical information to a visible form. The most common tool used to convert acoustical signals to electrical (visible) signals is an electromechanical transducer that uses a piezoelectric (pressure/electric) element as the active portion that would be responsible for this conversion to take place. The image produced can be processed and displayed in a manner very similar to optical signals.

Ultrasonic waves such as those used routinely during medical examinations and prognoses propagate in a very complex manner. This level of complexity holds true even when these sound waves propagate in ideal, homogeneous and uniform media. Despite the fact that diagnostic ultrasound techniques are based on well-established phenomena, dentistry remains an area where ultrasound has not yet played a very important role. This is due to the fact that ultrasonic propagation in homogenous/multi-layered media (such as teeth) results in further degradations in the acoustic field. Scattering effects at the micro-scale level as well as at the multilayer interfaces are responsible for these degradations. Proper calibration and post-processing of produced images helps in reducing these artifacts.

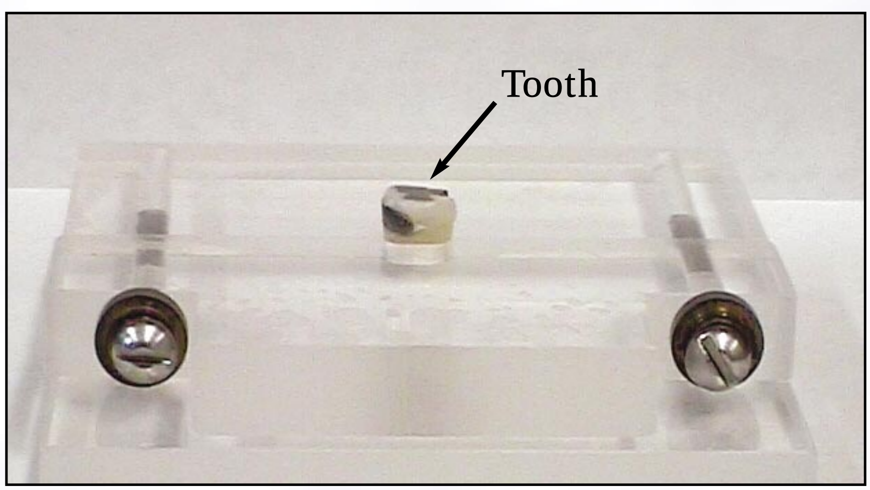

Figure 1. Plexiglas™ "tooth holder"

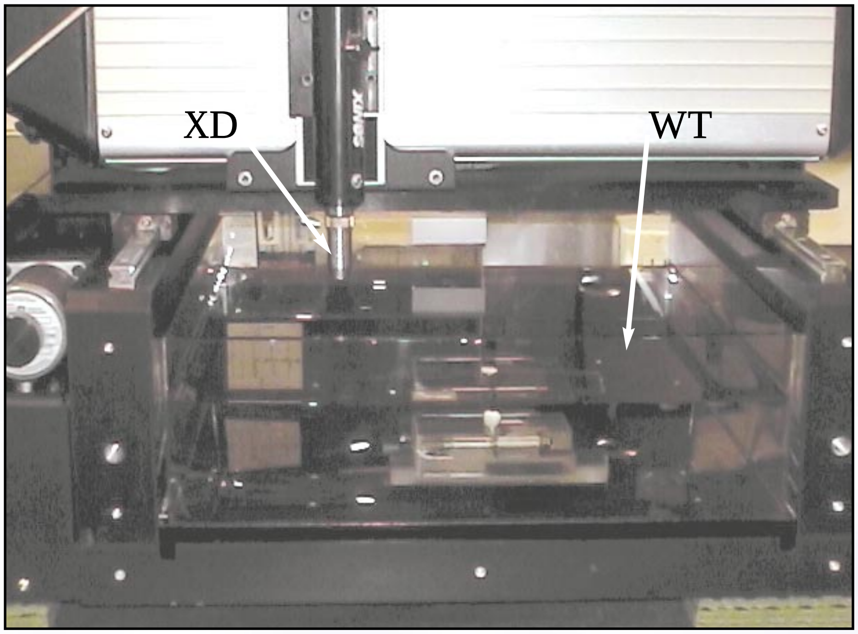

Figure 2. Experimental setup showing ultrasonic transducer (XD), water tank (WT) and immersed tooth holder (TH)

Experimental Setup

In this study, extracted human teeth are tested using water as the coupling medium (similar to the gel that is used in obstetrics for fetal monitoring, in cardiology for observing cardiovascular health, etc.). A scanning acoustic microscope (for high-frequency ultra-sound applications) is used for all experiments. It is important to note that high frequency is employed here because we are dealing with a small-size target. A single 10 MHz (10 million cycles per second) transducer is set up in a pulse-echo mode (meaning the same transducer transmits and receives the propagating signals). The driving source is a pulser/receiver that initiates the main voltage "bang" across the piezoelectric element inside the transducer, and receives the "transducted" return pressure pulse from the same transducer for display and further processing. The transducer is immersed in a tank filled with distilled water. A Plexiglas™ "tooth holder" (see Figure 1) was machined to hold the tooth under test in either an upright position with the top of the tooth (the crown) facing the radiated acoustic field, or in a lateral position with the tooth lying on its side. The holder with the tooth is immersed in the water tank. Figure 2 shows experimental setup located in the Biomedical Research Laboratory in Weed Hall. Figure 3 depicts the three teeth under examination.

Experimental Results

In earlier studies, mathematical finite element modeling and transmission line techniques based on circuit simulation were implemented in order to determine the robustness of this new diagnostic method and to describe, and therefore understand, acoustic field simulation, propagation and interaction with the internal layers of these complex teeth structures. Results in this study confirm these models and support the hypothesis that ultrasound can be a viable diagnostic tool in dentistry.

One-dimensional (amplitude versus time) *A*-scans and two-dimensional (amplitude versus depth) sector *B*-scans are collected when all teeth are mounted in the upright position in such a way that the surface of the enamel and/or the amalgam first encounter the ultrasonic radiation field. A total of six tests were conducted using the experimental setup described above. Thicknesses of the enamel and dentin layers are estimated from the time-of-flight (the time it takes the ultrasonic wave to travel from the transducer through the tooth and back) information in the *A*-scan obtained for the intact tooth. The two-dimensional sector profiles are obtained from the *B*-scans in order to observe the effects of wave interaction with the layers and tubular features in teeth, and to accurately locate the position of anomalies such as cracks, disbonds, etc. Figure 4 shows a typical *A*-scan signature (taken for the intact tooth); and Figure 5 illustrates the two-dimensional profiles of the resulting *B*-scans for the normal tooth, the tooth with amalgam, and the one that contains the cavity.

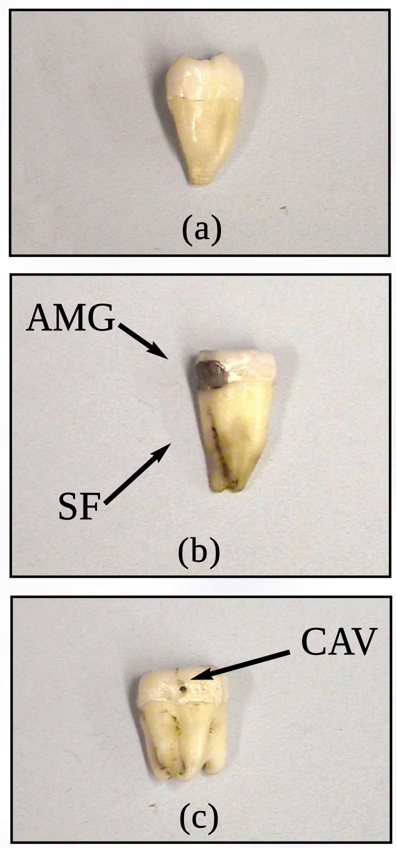

Figure 3. The three teeth under test: (a) intact tooth, (b) tooth with amalgam (AMG) restoration and surface fissure (SF), and (c) tooth with machine side-drilled hole that mimics a cavity (CAV)

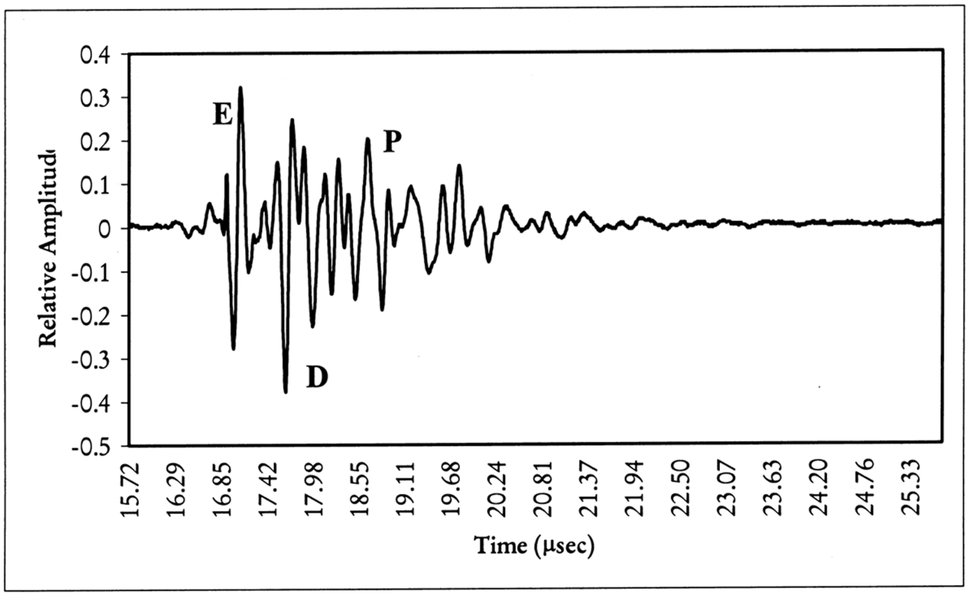

Figure 4. Typical *A*-scan of normal tooth illustrating several reflections, including (*E*) Enamel, (*D*) Dentin, and (*P*) Pulp Cavity

Discussion

The time-axis in the *A*-scan shown in Figure 4 represents the round-trip time it takes for the wave to travel through the multilayered tooth. Examining more closely this *A*-scan signal, one can get a limited but crucial set of information. Although it is difficult for the untrained eye to obtain from the figure shown, the three largest peaks located at 16.96 msec (10^{-6} seconds), 17.60 msec, and 18.60 msec, correspond to reflections of the sound pressure off the surface of the enamel, the dentin, and the pulp chamber layers, respectively. Using velocities of sound of 6250 m/s for the enamel and 3800 m/s for the dentin, the enamel-dentin and the dentin-pulp layers can be calculated from a simple relationship (thickness = (time/2) x velocity). The values are approximately 2 mm and 1.9 mm, respectively, which match closely the anatomical thicknesses of these layers as reported in earlier studies. On the other hand, a close look at the *A*-scan signal produced from the restored tooth (not shown) reveals no similar information about the layers. Rather, this information "vanished" because of the presence of the amalgam;

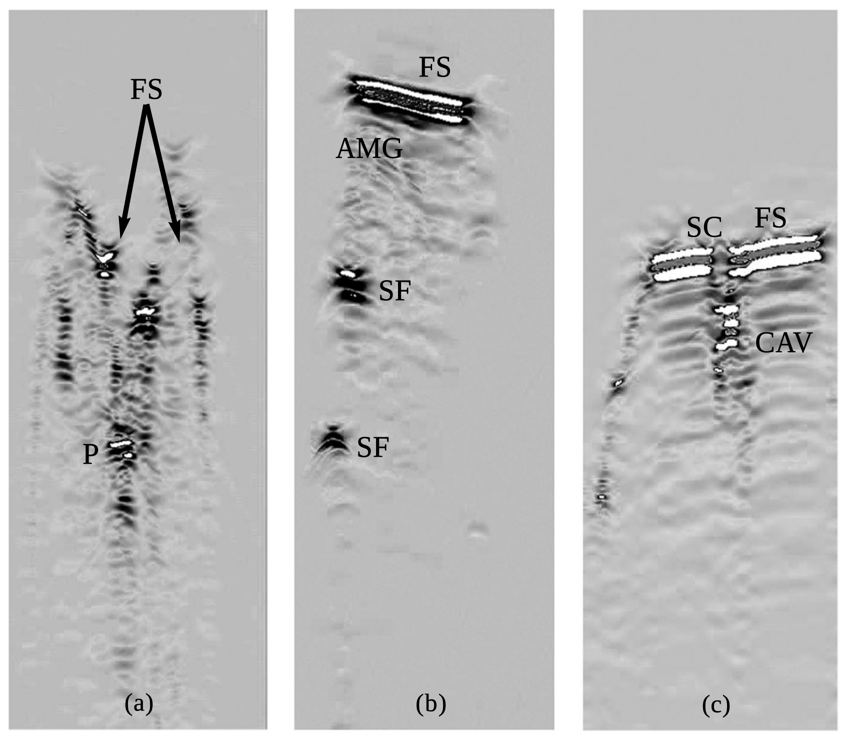

Figure 5. *B*-scans of (a) normal tooth showing natural curvature of front surface (FS) and pulp (P), (b) tooth with amalgam (AMG) restoration and surface fissure (SF), and (c) tooth with side-drilled cavity (CAV) and natural surface crack (SC) along the front surface (FS)

however, a reflection from the surface crack is prominent. This is expected due to the fact that the restoration in this particular case happens to extend deep and covers pretty much the whole volume usually occupied by the enamel and dentin layers. As a result, the only major feature that is going to be interrogated, and therefore reflected off, is the surface fissure that extends along the exterior façade of the tooth as demonstrated in Figure 3(b) and confirmed in Figure 5(b). Also, in the case of the tooth containing the "artificial" cavity, the *A*-scan (not shown) again reveals a protruded reflection from the cavity, which happens to be somewhat masked by the natural enamel layer in its vicinity.

Moving to the analysis of the *B*-scans (Figure 5) we see that these results match very closely what is observed in the *A*-scan signatures for all teeth. In the intact tooth case (Fig. 5(a)) the acoustic wave seems to travel throughout the medium in a normal fashion. This is noticeable in the family of reflections recorded from the various internal features and tubular structures within the tooth. It is very interesting to observe the natural curvature of the front surface that is first insonified by the radiation field. Furthermore, and as anticipated, a trained eye is able to decipher a number of derivative wave components (so-called shear, surface, edge, longitudinal, etc.) that have generated as a result of "mode conversion" that the longitudinal wave (one in which the particle motion is in the same direction as the wave propagation), initially launched by the transducer, has undergone when it encountered this highly anisotropic/inhomogeneous medium. Constructive as well as destructive interference can also be detected as a result of having this whole "symphony" of waves reflect and refract from this complex inner formation, as governed by the superposition principle (where signals add or subtract when they are present simultaneously). Looking at Figure 5(b), one can recognize the obvious change in reflection pattern when amalgam has been introduced as described earlier. This change is manifested by the fact that ultrasound now "sees" only a uniform composite until it reaches the surface crack, at which point a great mismatch in material properties (amalgam to water) causes a strong reflection to be marked along the transmission path. Figure 5(c) exhibits the third and last case of this study. The main feature here is the side-drilled cavity along the enamel-dentin boundary. In addition, a natural surface "crease" is present on the surface of the tooth just above the cavity. As seen in the figure, these defects can be easily recognized along with other normal wave reflections, representing mode conversion as discussed.

Finally, the spatial-peak temporal-average intensity (a measure of exposure to ultrasound) has been calculated using the *A*-scans produced in this study. Due to the non-theoretical nature of this article, mathematical formulations are bypassed for ease of understanding. It suffices to mention that this figure has been calculated to be 728.76 mW/cm^2 (milliwatts per square centimeters), which is pretty close to the worst-case regulatory limit of 720 mW/cm^2 for exposure criterion for medical diagnostic ultrasound imposed by the FDA.

Conclusion

It is evident from this experimental investigation that ultrasound can be a very useful technique in assessing the integrity of teeth. Furthermore, the results at hand demonstrate the ease of use of this procedure, not to mention the safety level associated with its non-ionizing nature and substantiated by the figure of merit that is in harmony with FDA protocol. Of course, further comprehensive laboratory studies, *in vivo* as well as *in vitro*, need to be implemented to cover other tooth anomalies in order to corroborate the validity and viability of this new diagnostic tool. Once this is done, plans can be made to manufacture products based on this technology. Are there any potential capital investors in the house?

Sleiman Ghorayeb has always been intrigued by noninvasive means of looking at places where light cannot penetrate or does not exist. He explains, "Gamma rays, X-rays, microwaves, ultrasonic waves, and other modalities of propagating energy are used for this purpose . . . ultrasonic waves are my favorite for they are the most natural and least hazardous."

Dr. Ghorayeb earned a B.S. and M.S. in electrical and computer engineering, an M.S. in biomedical engineering, and a Ph.D. in electrical and computer engineering with emphasis in biomedical research from Iowa State University. The overwhelming use of ultrasonic waves since the mid-20th century in medical imaging and non-destructive testing of otherwise unobservable targets played a very important role in his decision to pursue a field that links engineering and medicine — biomedical sciences.

Prior to joining the Hofstra faculty in fall 1996, Dr. Ghorayeb served as affiliate faculty member at Iowa State University where he was the recipient of the Teaching Excellence Award, and held an administrative position as Director of Engineering at one of Iowa State University's offshoot companies located in its research park. He also held collaborative research positions with the Dental Research Institute at the University of Iowa, Center for Nondestructive Evaluation at Iowa State University, U.S. Army Aviation Applied Technology Directorate, McDonnell Douglas Helicopter Systems, and ABB Vetco Gray Sensors Group.

Currently, Dr. Ghorayeb serves as Director of Industry Relations in Hofstra's Department of Engineering. Dr. Ghorayeb maintains strong collaborations with North Shore-LIJ Health System, Winthrop University Hospital, Brookhaven National Laboratory, Underwriters Laboratories, Misonix, and Koehler Instruments, all of which are located on Long Island.

Dr. Ghorayeb's research interests are in the fields of diagnostic, surgical and therapeutic ultrasound, finite element modeling, and general noninvasive testing and evaluation. He has authored numerous journal articles as well as conference proceedings reporting his research findings. -SK