ARTIFICIAL INTELLIGENCE ALGORITHMS FOR THE ULTRASONOGRAPHIC PERIODONTAL PROBE
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Abstract
Periodontal disease, commonly known as gum disease, affects millions of Americans. The current method of detecting periodontal disease is painful, invasive, and inaccurate. As an alternative to manual probing, the ultrasonographic periodontal probe is being developed to use RF ultrasound waveforms to measure periodontal pocket depth, which is the main measure of periodontal disease. The methods employed use wavelet transforms and pattern recognition techniques to develop artificial intelligence routines that can automatically detect pocket depth. Applying ultrasound to dentistry in this way is useful for long-term flight situations in the space industry.

Introduction
In the clinical practice of dentistry, radiography is used to detect subsurface structural defects such as cavities and cracks. However, radiation is harmful to the patient, and has been shown to actually lead to cavities by the demineralization of teeth. Radiography can also only detect defects parallel to the projection path, and it is useless for detecting conditions such as gum disease because soft tissues are transparent to x-rays. Ultrasonographic Nondestructive Evaluation, however, is safe to use as often as indicated, and computer interpretation software makes diagnosis automatic. The structure of soft tissues can be analyzed effectively with ultrasound, and even symptoms such as inflammation can be registered with this technology.

One application of ultrasound (US) in dentistry, a periodontal probe, is already being developed as a spin-off of NASA technology. Periodontal disease is caused bacterial infections in plaque, and the advanced stages can cause tooth loss when the periodontal ligament, which usually holds the tooth in place, erodes. The usual method of detection is with a thin metal probe lined with gradations marking depth in millimeters (Fig. 1a). The dental hygienist inserts the probe into the area between the tooth and gum to measure the depth to the periodontal ligament. This method is only accurate to +/- 1 mm and depends upon the force the hygienist uses to push the probe into the periodontal pocket. Furthermore, this method is painful and often causes bleeding. The ultrasonic periodontal probe currently under development...
development uses high-frequency ultrasound to find the depth of the periodontal ligament non-invasively. An ultrasonic transducer projects high frequency (10-15 MHz) ultrasonic energy in between the tooth and the gum and detects echoes of the returning wave (Fig 1b). Since water is used as a coupling agent, the depth of measurement can be calculated by multiplying the time delay of the echoes by the speed of sound in water (1500 m/s).

Materials and Methods

Previous publications describe the fabrication of the 5th generation prototype ultrasonographic probe itself. The shaft of the probe is manufactured similarly to other dental handpieces, and the 10MHz piezoelectric transducer located in the head of the probe was manufactured by Imasonic. Water is the coupling agent, so the fabrication of the probe allows water to be funneled through the custom-shaped tip. The rest of the equipment used to control the probe, including the pulser-receiver and the water flow device, are shown in Figure 2.

Simulations

Before testing the probe on actual patients, computer simulations were performed by our group. The simulations projected sound energy reflecting from all the important tissues in a simplified tooth anatomy. The simulation returns a 2D cross-section of the power spectrum being received by the transducer as well as an RF waveform such as would be recorded by an actual transducer. A sample waveform is shown in Figure 3. It is important to note that no echo from the periodontal ligament was recorded; therefore the technique described above – calculating the depth of measurement by multiplying the time delay of the echoes by the speed of sound of the medium – may not be feasible.

Clinical Trials

Clinical trials were performed between April and May of 2007 with the assistance of ODU's Dental Hygiene Research Center on 12 patients (Fig 4). We assisted with the computer interface and with the dental hygienists operating the probe in order to assure that the data is of high quality. Throughout the rest of the year, we developed the artificial intelligence (AI) algorithms to automatically interpret the ultrasonic echoes in real time.

Data Analysis

Like the simulation data, the waveforms recorded from the clinical trials do not show any significant reflection from the periodontal ligament. Therefore, other mathematical techniques must be applied. The signal-analysis technique called Dynamic Wavelet Fingerprinting Technique (DWFT) will be used to determine the pocket depth. This technique applies a wavelet transform on the original signal, which results in “loop” features that resemble fingerprints (Fig. 5). By applying different wavelet transforms and filtering techniques, as well as pre-existing fingerprinting classification technology, our research for the periodontal probe will focus on trying to find a pattern in the fingerprints that indicates the depth of the periodontal ligament.

After applying the wavelet fingerprint technique to the waveforms, the next step is to apply image recognition techniques to measure properties of each fingerprint. Some of these properties include fitting an ellipse matching the second moments of each fingerprint and measuring such aspects as eccentricity and...
orientation. Other properties measured include coefficients of second- or forth-order polynomials fitting the boundary of the fingerprint, or simpler measurements like area or height. In total, we evaluated a combination of 2016 different wavelets, features, and selection criteria. Because of the enormous computation time of this task, the computer algorithms were adapted to run on William and Mary’s Scientific Computing Cluster (SciClone).

Results and Discussion

With wavelet fingerprint properties gathered from the clinical trial data, the goal is to develop an artificial intelligence algorithm that correlates wavelet fingerprint properties with pocket depth. Two techniques have been applied to find such an artificial intelligence algorithm: creating a lookup table from the measured fingerprint properties, and applying well-known pattern recognition techniques.

Lookup Tables

To create the lookup tables, the weighted average of the largest values of a particular fingerprint property was calculated. Figure 6 below shows the distribution of this weighted average fingerprint property versus measured pocket depth. In this technique, only the files with the fingerprint property that that stays fairly constant over repeated sampled waveforms were selected, so at most 75% of the available data was plotted here. Once the lookup table is created for a particular wavelet fingerprint, window size, and selection criteria, the artificial intelligence routine operates by performing the weighted averaging on a particular waveform and looking for that value in the table. It returns the probability that the waveform corresponds to a range of manual probe values. Figure 7 shows a graphical representation of the returned probabilities. The number in the upper right hand corner corresponds to the manual probe value, and the x-axis corresponds to probable pocket depth. The color intensity corresponds to probability. As can be seen, the higher probabilities line up in a column roughly corresponding to the manual probe value.

However, the lookup table routine has one major flaw. For any particular waveform, the value of the averaged fingerprint property appears in the lookup table itself. Using instead a leave-one-out routine, where the lookup table is created for each waveform by removing that waveform's property value from the lookup table, the results are much less promising (Fig. 8).

Pattern Recognition

Pattern recognition routines can take measured values and correlate them with known labels. Unfortunately, the data returned from the wavelet fingerprinting process consists of two
dimensions, namely, one dimension for the fingerprints obtained from one waveform and another for repeated waveforms that were continuously recorded at the same tooth site. The pattern recognition software (PRTools, a package of pattern recognition algorithms for MATLAB) requires a single measured value. To collapse the two dimensional data to a scalar, the change in the repeated waveforms was measured and then the turning points were gathered. Different measured values of the turning points were selected for the pattern recognition routine. Turning points were suggested from comparing hard and soft tissue interface simulation waveforms.

Next, many combinations of pattern recognition maps were analyzed, including a single map, combinations of maps, and selecting the best features from the available turning point measurements before applying the pattern classification. The accuracy of these routines peaks at about 40%, but easily 80% of the returned files are within 1 mm of the manually measured pocket depth value, which matches the precision of the manual instrument. However, that number is deceiving because of the distribution of the manual probe data is such that 64% of the data are in the 2-3 mm range, so saying that 80% of the data is within 1 mm does not actually describe how well the pattern recognition routines work. Figures 9-10 below show some sample pattern recognition results.

**Conclusion**

The method of applying wavelet fingerprints to the periodontal probe data and then attempting pattern recognition routines seem promising. Further work needs to be done before we can conclude that the method does not work. However, it is important to keep in mind that the data set involved consists mostly of healthy periodontal samples. A more diverse trial data set, and more data in particular, could help in identifying a satisfying detection algorithm. Future work involves obtaining more data, as well as analyzing the simulations for power returns from the bottom of the pocket.

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**Figure 7: Lookup table results.** Actual pocket depth (upper right-hand corner of each figure) is plotted versus predicted pocket depth. Color intensity represents probability. Note that the actual pocket depth and predicted pocket depth tend to match.

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**Figure 8: Actual vs. Predicted pocket depth.** The lookup table technique was tested here with a leave-one-out routine, showing less success than in Fig. 7.
Figure 9: First example of pattern recognition results. Shown is a) a histogram of the difference between actual and predicted labels, and b) a chart of actual versus predicted pocket depth. The map used here was a quadratic discriminant map on the 3rd quadratic coefficient fitted to the boundary of the fingerprints. The map yields 77.8% of the files within 1mm of the correct pocket depth. The histogram suggests good results but the chart points out that those results work only for the 2-3 mm pocket depths. Note that the higher pocket depths are not even predicted.

Figure 10: Second example of pattern recognition results. As above, a) is a histogram of the difference between actual and predicted labels, while b) shows the chart of actual versus predicted labels. The map used here is k-nearest-neighbor on Eccentricity, with 78.8% of the files correct to within 1mm. But the chart shows an even worse distribution of predicted pocket depths.

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2 Differential measurement periodontal structures mapping system, United States Patent 5755571, Companion, John A., The United States of America as represented by the Administrator NASA