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SMART TOOTH SYSTEM FOR IN-SITU WIRELESS PH MONITORING

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ABSTRACT

In this paper, we introduce an oral motion-powered Smart Tooth system that can monitor oral health. Lower pH is an indicator of bacterial accumulation in the oral cavity, which can cause tooth decay, periodontal or peri-implant diseases. Thus, in situ monitoring pH inside of the mouth is critical to prevent oral diseases. Using a piezoelectric dental crown, Smart Tooth system converts oral motions, such as chewing, to electrical power which can impinge a surface integrated LC transponder. The LC transponder also incorporates iron oxide nanoparticles-embedded pH-sensitive hydrogel that modulates the resonant frequency via shrinking or swelling. As a proof of concept, the fabricated prototype measures pH levels ranging from pH 4 to 12 and sends data wirelessly to the receiver placed up to 5 cm away (wireless transmission path loss at 3 cm was 50.79 dB). The results indicate that the Smart Tooth system can monitor oral health while replacing missing teeth.

KEYWORDS

Dental; pH sensing; hydrogel; piezoelectric; bio-telemetry; LC transponder; wireless healthcare monitoring.

INTRODUCTION

Smart health care has been transforming disease management in many ways, enhancing the diagnostics and treatments to be more efficient, convenient, and personalized. Notably, wireless sensing systems have led to new insights in developing continuous monitoring due to recent advances in low-power interfaces, RF electronics, and miniature power sources. Such a system also increases patients' mobility, enables early disease detections, and reduces the overall healthcare cost in the long run. A good example is the PillCam, a pill-shaped wireless endoscopy with an advanced imaging system (e.g., white LED, micro-lens, CCD sensor).

The use of resonant passive transponder for sensing and monitoring has been utilized to measure physiological parameters, such as pressure, pH. For example, pressure in the intracranial, intraocular, bladder, and artery could be monitored wirelessly [1]–[3]. These wireless sensors use a passive LC (inductor and capacitor) resonant circuit to translate the pressure or biochemical information to an electrical signal. Pressure applied to a movable plate of capacitor or pH solution interacted with chemomechanical hydrogel (swelling or shrinking) that carries higher magnetic susceptibility placed on the inductor could modulate the overall resonant frequency of the LC transponder [4]. However, wireless transmission of the data requires a complex readout system to energize the sensor with high energy and read the reflected signal. Such an approach poses challenges in the interrogation range (usually extremely short < 1 cm) and suffers from thermal issues due to the use of high energy. This has been one of the main reasons that, so far, very few or no such systems have been utilized in dental/oral health applications.

The key indicator of oral health is pH level. Common oral diseases, such as dental caries, periodontal or peri-implant diseases, are associated with local bacterial accumulation, which induces acidic pH due to their metabolic activity. Healthy adults usually maintain the neutral pH in the oral cavity [5]. However, when bacteria colonize and dental plaque grow, pH plummets below 5.5 conducive to tooth decay. Then, these bacteria clumps migrate toward the interface between gingival tissue and natural tooth/implant crown, ensuing tissue inflammation [6]. In this paper, we report a Smart Tooth system that can monitor pH level inside of the mouth using an oral motion-powered LC transponder with pH-sensitive ferrogel. The Smart Tooth system is expected to overcome many of the abovementioned shortcomings in a passive transponder, i.e., short interrogation range, complicated readout instruments, and thermal effect.

WORKING PRINCIPLE

Figure 1 illustrates a schematic of the Smart Tooth system for *in situ* real-time pH monitoring. It comprises three modules: a piezoelectric dental crown as a source of power, a pH-sensitive hydrogel with ferromagnetic nanoparticles as a sensing element, and an LC (inductor-capacitor) transponder for wireless sensor readout. Upon an oral motion (e.g., chewing, tooth brushing, mouth washing) strikes the piezoelectric dental crown, an instant electrical power is exerted. This momentarily charges the capacitor of the transponder (charging phase). When the stress is released from the crown, the charging phase ends and begins the radiation phase, in which the transponder initiates the oscillation between capacitor and inductor. Such oscillation radiates electromagnetic waves through the inductor (antenna), which can be captured from outside using a simple receiver coil. The electromagnetic waves carry pH information in the form of the resonant frequency. For that, pH-sensitive ferromagnetic hydrogel that exhibits chemomechanical behavior (i.e., swells at higher pH and

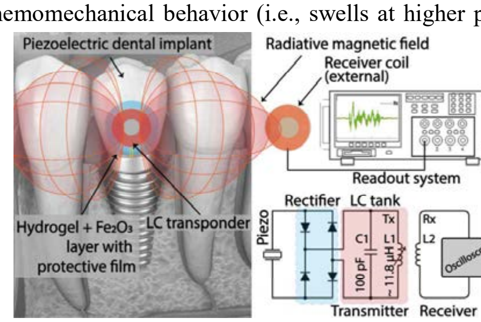

Figure 1: A schematic of Smart Tooth showing wireless pH monitoring

shrinks at lower pH) was deposited on the inductor. Particularly, the ferromagnetic nanoparticles embedment alters the overall permeability depending on the environmental pH level, resulting in resonant frequency shifts. The radiation phase lasts until all stored energy from the charging phase is discharged through wireless signals or another charging phase begins. As such, the received signal appears to have a damping nature. Figure 1 subset shows a circuit diagram of the smart dental sensing system. A full bridge rectifier circuit integrated into the system converts AC power from the piezoelectric dental crown to a DC power, which charges the LC transponder with a hydrogel pH sensing element. As for the readout system, a simple instrument such as an oscilloscope with a receiver coil can sufficiently capture the radiating EM waves.

MATERIALS AND METHOD

Figure 2 shows the fabrication process for a prototype Smart Tooth system. It starts with synthesizing a pH-sensitive hydrogel, as described in Song et al. [4]. The hydrogel solution has two parts: solution A is prepared by mixing 334.5 mg of acrylamide with 100.8 μL of methacrylic acid, 100 μL of N,N,N′,N′-tetramethylethylenediamine accelerator, and 16.35 mg of N,N′-methylenebisacrylamide crosslinker, dissolved in 1.2 mL of deionized (DI) water; solution B is prepared by adding 16 mg ammonium persulphate to 0.2 mL of DI water. Adding part A to part B initiates crosslinking of hydrophilic polymer chains provided by the acrylamide polymer base. The hydrophilic elements attached to the polymer allow hydrogel to absorb water while the cross-linking between the polymer chains prevents dissolution. Electrostatic repulsion between the ionized groups (carboxyl groups of methacrylic acid) can be modulated due to the presence of H^+ ions in the solution, which in terms can control the amount of shrinking at low pH or swelling at high pH of the hydrogel [7]. To functionalize the ferromagnetic function in the pH-sensitive hydrogel, 9.01 mg of iron (III) oxide (Fe_2O_3) nanoparticles (5 wt.%, < 50 nm, $\mu_r > 1$) are mixed in 154 μL of solution A. After 5 min of vortex mixing to obtain uniformly dispersed nanoparticles, 26.1 μL of solution B is added to solution A (5.9: 1 ratio), completing the pre-gel solution for ferrogel (Figure 2a-2b) [4]. After 5 seconds in a vortex mixer, the pre-gel solution is poured over the organosilane coupling agents (γ-MPS) treated medical-grade pressure-sensitive adhesive (PSA) (AR Seal, Adhesives Research) shown in Figure 2d. The PSA is laser machined to create access holes for environmental fluids to interact with the hydrogel (Figure 2c). The PSA with ferrogel was then bonded with a planer inductor coil. The inductor coil (L) is made of polyimide insulated copper wire (thickness = 0.25 mm, N = 28) with a nominal inductance of 11.8 μH. The inductor is connected to a 100 pF ceramic capacitor to create an LC transponder. Thus, the resonant frequency of the LC transponder was calculated to be 4.63 MHz ($f_r = 1/2\pi\sqrt{LC}$). Lastly, the LC transponder with iron (III) oxide nanoparticle-embedded hydrogel is attached to the piezoelectric dental crown surface with the PSA along with the electrical connections (Figure 2g). It is noteworthy that our choice of PSA is a silicone-based adhesive that provides an immediate bond to low-energy substrates and resistant to organic solvents [8], [9]. To validate the proof of concept design, we integrated the LC transponder on a piezoelectric dental crown sample previously reported by Park et al. [10]. Such dental crowns can be fabricated by sintering barium titanate ($BaTiO_3$) nanoparticles. First, we prepared a binder solution by mixing polyvinyl fluoride (PVDF) in an organic solvent N,N-dimethylformamide (DMF) by a weight ratio of 1:8.8 in a water bath at 80 °C temperature, for 15 minutes. When the PVDF was completely dissolved, we added barium titanate ($BaTiO_3$) nanoparticles (400 nm, US Research Nano materials) and mixed them slowly to reach a high-volume concentration (as much as 332 wt.%). The colloidal gel with BTNp was then loaded into a syringe (10 mL, 600 μm nozzle) and affixed to an extrusion 3D printer (Culture 3Ds, Tissue Scribe) to print a dental crown structure at 1 mm/s speed with 400 μm z-axis resolution. The printed sample was then dried for 2 hours in an oven at 120 °C to evaporate the DMF. The dental crown was prepared for debinding and sintering in the post-processing phase, performed in a tube furnace (GSL-1500X, MTI Corporation). The sample was held at 650°C for 1 hour (ramp: 5°C/min) for debinding and at 1400°C for 3 hours for sintering (ramp: 5°C/min) followed by cooling down at -5°C/min rate. After sintering, it was poled with 1 kV/mm electric field for 4 hours at 80°C in a silicone oil bath to induce piezoelectricity by aligning randomly oriented ferroelectric dipoles in the sample.

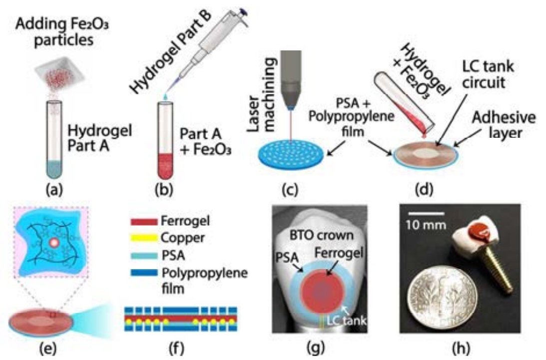

Figure 2: Fabrication process of a Smart Tooth: (a-b) preparing the pre-gel solution of ferrogel; (c-e) forming ferrogel disc on laser machined PSA (for fluid access); (f) cross-sectional view; (g) a proposed Smart Tooth; (h) a fabricated prototype.

As a proof of concept, we mimicked oral motion stress using an ultrasonic transducer (TX-0.5MHz-44mm, Precision Acoustics). Such stress should be within the range of force created from an electrical toothbrush (2-2.5 N) or, biting solid foods (average ~480 N) [11], [12]. Figure 3 shows an experimental setup. We used a water tank to mimic the biological acoustic impedance. The ultrasonic transducer was placed within the water tank. It was driven by a signal generator (4065, B&K Precision) accompanied by a 55 dB RF amplifier (1040L, E&I Ltd.). An input signal of 1 V and 310 kHz were propagated as three burst waves with 1 ms interval. The Smart Tooth was placed 8 cm away on a platform to receive ultrasonic waves. The average received stress was 428.32 kPa, measured by a fiber optic hydrophone (FOHS64, Precision Acoustics). This stress would be able to create about 42.83 N force on the smart tooth which is equivalent to biting on a biscuit [13]. The receiver coil was also placed inside the tank. The LC transponder was connected to an impedance analyzer (E5061B-005, Keysight Tech.) to observe the shifts in resonance frequency due to the pH change as we add different pH solutions to the water tank. The pH of the solution was also measured with a digital pH meter (AI311, Apera Instruments) for cross-referencing. The Smart Tooth sensor was submerged for at least 10 minutes in each pH solution before any measurements were taken. The receiver coil was connected to an oscilloscope (MSOX 3024T, Keysight Tech.) to record the wirelessly received signal.

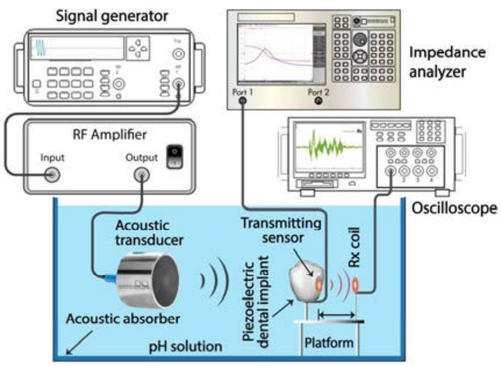

Figure 3: Experimental setup with an acoustic transducer as a stimulator.

RESULTS AND DISCUSSION

As discussed, mechanical stress (due to oral motion or ultrasound in our case) induces electrical power from the piezoelectric dental crown, which then drives oscillation in the LC transponder. Figure 4a shows the mechanical input to the Smart Tooth prototype. The pulses were amplified using the RF amplifier and converted to acoustic energy using the ultrasonic transducer. As the ultrasonic waves struck the dental crown, we measured the voltage generated from the dental crown (~ 400 mV) as shown in Figure 4b.

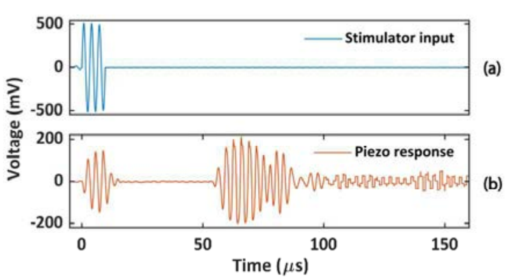

Figure 4: Example of Smart Tooth operation: (a) mechanical stimulation; (b) piezoelectric output

The voltage from the piezoelectric dental crown was then rectified and fed to the LC transponder. Specifically, the positive half cycle of the piezoelectric output from the dental crown charged the LC transponder. As soon as the piezoelectric output turns to negative (negative half cycle), the LC transponder starts electromagnetic radiation, as shown in Figure 5a. In our case, three bursts of ultrasonic waves were applied, which could induce synchronized three high-energy oscillations. These oscillations could be detected wirelessly using a receiver coil placed at a distance. Figure 5b shows an example of a wirelessly captured signal (~ 3 mV) at 1 cm distance using a receiver coil and an oscilloscope. The base resonant frequency could be confirmed through a fast Fourier transform (FFT) on the received signal, which showed 4.25 MHz, close to the theoretical value (Figure 5c).

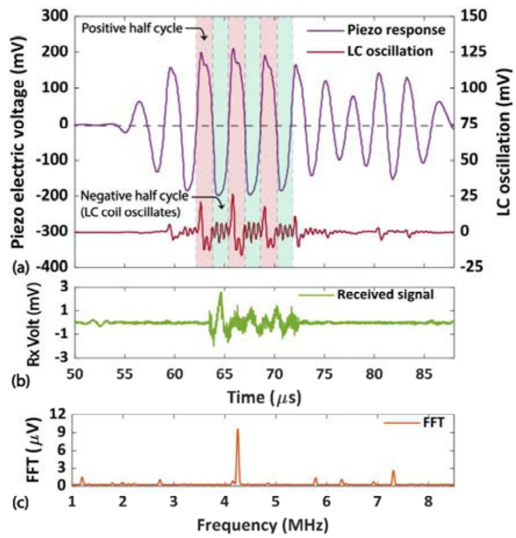

Figure 5: (a) Sequential charging (red) and radiation (green) phases of Smart Tooth system; (b) wirelessly received signal; (c) FFT of the wirelessly received signal.

The resonance frequency of the LC transponder shifts, depending on the swelling/shrinking of the ferrogel in response to the pH level of the medium. Thus, analyzing the resonant frequency information could be translated into the pH value. At higher pH, the ferrogel swells isotopically and form as a large disc on top of the planar coil. This swelled ferrogel covers the large area of the planar coil with higher permeability iron oxide, increasing the overall inductance as following.

$$L = L_0 + K(\pi \int_0^r R(x)^2 dx)$$

where L_0 is the intrinsic inductance of the coil, K is the proportionality constant, and $R(x)$ is the ferrogel swelling radius ratio as a function of pH level. As a result, the resonant frequency decreased. Figure 6 shows the change in the resonance frequency of the LC transponder in various pH levels. The additional inductance due to a three-dimensional ferrogel disc was measured to be in a range of 1.37 to 2.84 μH due to a full-scale pH change of 4.42 to 11.95. However, the sensing response exhibited three segmentations from pH 4 to 6, pH 6 to 9.6, and pH 9.6 to 12. It could be attributed to iron oxide nanoparticle embedment yields different swelling/shrinking ratios in these regions, requiring further investigation in the future.

After confirming the *in-situ* pH monitoring, we measured the wireless sensor data transmission up to 5 cm distance from the Smart Tooth to the receiver. The receiver coil was aligned horizontally and placed at a vertically

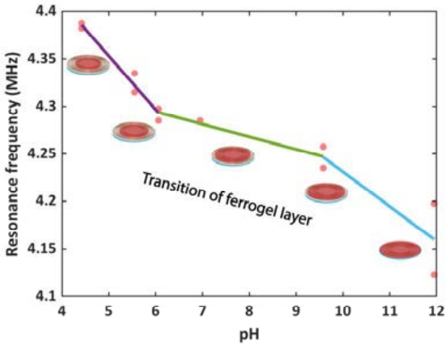

Figure 6: Resonance frequency vs. pH

centered position. A network analyzer (E5061B, Keysight Tech.) was used to measure the logarithmic ratio of the transmitted and received power (i.e., path loss) in the frequency range of 4 MHz to 5 MHz. Based on the result in Figure 6, the mid-frequency of 4.25 MHz was chosen to study the path loss. Figure 7 shows how distance impacted the transmission path loss. The Smart Tooth could transmit pH information wirelessly up to 3.5 cm distance with a path loss comparable to the theoretical path loss with magnetic induction communication [14].

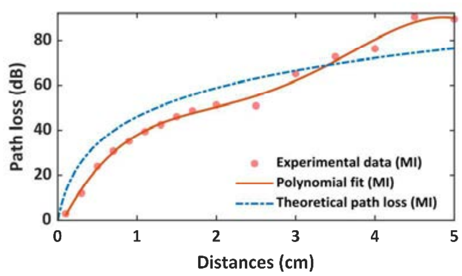

Figure 7: Wireless data transmission path loss for smart dental implant and compared to theoretical values.

CONCLUSION

A novel Smart Tooth system with piezoelectric dental crown integrated with *in situ* pH monitoring function is introduced. As a proof of concept, the device functionality and operation were demonstrated, which showed the expected response with respect to the pH changes. The wireless communication would add an extra layer of convenience for monitoring the overall oral health without any intervention. Thus, the Smart Tooth is expected to help with the early prevention and diagnosis of periodontal and peri-implant diseases.

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