

Dental pH Opti-Wand (DpOW): measuring oral acidity to guide enamel preservation

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Abstract— Undetected caries can lead to painful cavities and surgical restorations. Lack of proper detection tools makes caries prevention dependent on dentist's expertise and presents obstacles in oral health monitoring. To overcome this problem, we have developed a new approach to predict early stages of enamel demineralization caused by oral bacteria. These bacteria metabolize sugars in our food and produce organic acids that lead to cavities. Measuring the acidity level can help predict early stages of tooth decay. pH paper or pH electrodes can be used to monitor acidity, but neither are able to track pH levels in all dental locations. Our device, DpOW, is a non-contact optics-based pH device that uses changes in the spectral fluorescence of FDA allowed fluorescein dye to measure acidity levels in difficult to access dental locations such as occlusal fissures. A prototype has been tested over a wide pH range (7.12 to 3.89) and shown to track the change in pH with 0.94 correlation coefficient.

I. INTRODUCTION

Dental caries, also referred as tooth decay, is the most common chronic infection in children, affecting 18.6% of children in the US between 5 and 19 years [1] and 2.4 billion worldwide [2]. The caries process starts with an oral biofilm and its adherence to the enamel, continues with acid-induced enamel surface demineralization, and finally progresses into a deeper infection of the underlying enamel that leads to cavitation. At home, a low sugar diet and dental hygiene are required to prevent caries, which includes 2-minute brushing sessions twice a day, flossing, and exposure to fluoride [3]. At the dentist' office, the standard-of-care is for the removal of oral biofilm deposits or plaque at 6-month intervals and the inspection of the teeth for early (demineralization) and later stages (cavities) caries using direct visualization. The dentist also relies on x-ray imaging and haptic response from probing the teeth with a metal pick. Recently, more dentists have been applying preventative therapies, such as sealants and fluoride varnish, but there is no visual or x-ray means to predict where caries will arise. In the caries process, the biofilm generates organic acids from the metabolism of fermentable carbohydrates and sugar. These acids penetrate



Fig 1. Top and bottom view of DpOW

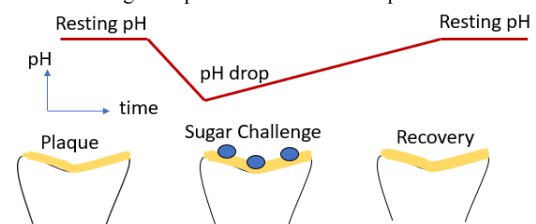


Fig.2. Stephan's Curve showing pH drop and recovery after glucose rinse which takes 30 to 120 mins. Plaque is depicted in yellow and pH measurement spots in blue.

the outer enamel surface and dissolve the enamel calcium hydroxyapatite mineral. A deeper bacterial infection can occur if this wearing is left undetected. In 1944, Robert Stephan showed that the pH of dental plaque sharply drops after transient sugar exposure and is restored back to a baseline pH in about 30 min on healthy enamel; infected enamel takes 120 min to recover. The return to a near neutral pH is facilitated by the buffering action of circulating saliva. Long term exposure to acidic pH below 5.5 leads to demineralization of enamel [4, 5].

Lingström et al. compared three different methods of measuring pH intraorally and concluded that each method produced similar relative rankings of the plaque deposits based on pH, but the absolute values of these pH values were dependent on the kind of measurement that was taken [6]. For example, a microelectrode contacting the exterior of the plaque deposit gave higher pH readings than a measurement between plaque and substrate, as expected. However, such an approach disturbs biofilms and is impractical for routine use in the dental clinic. Carlén et al. showed that a simple pH indicator strip can be used to measure plaque pH in interproximal dental plaques with a 0.99 correlation coefficient to a pH microelectrode [7]. Although this is an inexpensive and rapid method for plaque pH testing, it is slow and does not measure along the gum line or fissures along the biting surfaces. Thus, there is an unmet need for rapid, non-contact, quantitative measure of dental plaque pH.

We propose a novel method that optically measures the pH surrounding the oral biofilm using a device that has a

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toothbrush-like form factor. This device (**Fig. 1**) helps determine the ‘activeness’ of plaque which can help clinicians objectively decide on the future occurrence of dental caries at that specific location. We use a pH-sensitive fluorescent dye, fluorescein (FL), that is FDA approved and is used as a plaque “disclosing agent” in routine dentistry [8]. FL’s emission spectrum changes with pH, helping us determine the local pH of the plaque. The device tracks pH between 4 and 7, using two pulsating light emitting diodes (LEDs) (405 and 470 nm peak wavelength) and a photodetector sensitive in the 500-525 nm range. We validated our device using FL in different standard pH solutions and extracted human teeth, which demonstrated that we can measure relative pH changes between 4 and 7 with a 0.94 correlation coefficient. In a clinical setting, patients would rinse their mouth with FL to measure resting pH and then use a sugar solution to monitor the acid activity level of their biofilm, which serves as a proxy of incipient caries.

II. BACKGROUND

A. Oral Bacterial Activity

Plaque pH is associated with early caries [5]. If the plaque is bound to sound enamel (no demineralization), then the pH drop following a sugar rinse would be low in magnitude and recover to a near-neutral pH in a short amount of time (~20 min). However, if the plaque is associated with some degree of caries activity or demineralization, then the resting pH will be below 7, the rapid drop in pH will reach a lower level, and the duration of the low pH trough will be longer (**Fig. 2**). By ranking all suspicious plaque deposits by their resting pH and/or their response to a sugar challenge, the most susceptible dental locations may be identified.

B. Fluorescein

FL has four optically absorbing species in aqueous solution, and the concentration of each species is pH dependent [9]. The dianion form has peak absorption at 490 nm but has the lowest absorption of all 4 species at 405 nm. In the 4 to 7 pH range, the dianion and anion have

overlapping emissions within the 500-525 nm bandpass of the photodetector.

C. Dental Autofluorescence (AF)

Human teeth are naturally autofluorescent (AF) under illumination by ultraviolet to blue light excitation with a red-shifted peak emission peak at 475-nm along with a broad red-emission tail [10]. The AF emission is not considered pH dependent for sound and early caries teeth since the AF collagen species is likely concentrated below the enamel surface at the dentin-enamel junction.

III. DEVICE

A battery powered pH detector is designed to excite both the pH sensitive FL dye and teeth AF at 470 and 405 nm, respectively. The single emission detection channel of 500-525 nm uses a filtered silicon photodiode. The overall signal flow diagram of the system is summarized in **Fig. 3(a)** and is described in detail below.

A. Hardware

1) Optical and Mechanical Design

The device was 3-D printed in PLA-plastic to house the printed circuit board (PCB), battery, and the optical filters. **Fig. 3(b)** shows the computer-aided design (CAD) drawing of the device in SolidWorks. Two LEDs are used as excitation sources: one at 405 nm (Everlight Electronics’ EAUVA35353) and another at 470 nm (Broadcom Limited’s ASMT-BB20-NS000). The LEDs are placed on the two sides of a beam splitter (Edmund Optics, #68-545) to ensure that their output overlaps. The 470 nm LED, which has higher power output, is placed on the 30% transmission edge of the beam splitter; the weaker 405 nm LED is on the 70% reflection edge. There is a 492 nm sharp cut-off, short pass filter (Semrock, #FF01-492/SP-25) under the beam splitter facing the 470 nm LED to block leakage into the emission band from the excitation light source. The tip of the device is slightly angled so that the optical axes cross at a point about 1” from the wand as seen by the LEDs and the photodetector. The photodetector has two 25 nm wide

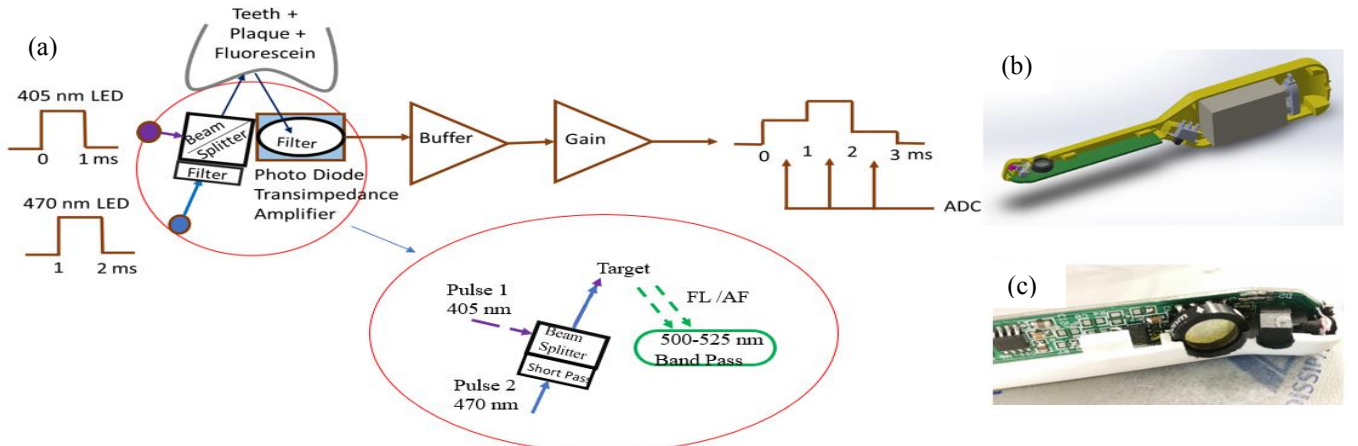


Fig. 3. (a) Signal flow of the pH detector with detailed optical path inset. Alternating pulses of 405 and 470 nm used to excite teeth (AF) and fluorescein (FL). Filtered and amplified photodiode signal is collected by an ADC of the microcontroller (b) CAD Design (c) PCB Board with optics

bandpass filters centered at 512 nm to reject LED excitation (Edmund Optics, #33-323, 12.5-mm). All non-optical surfaces are blacked out using black paint to reduce reflection and leakage of source light into the filtered photodetector.

2) Electrical Design

The two excitation LEDs, 405 nm and 470 nm were sequentially pulsed at 300 mA and 20 mA respectively using constant current LED drivers (Infineon Technologies' TLE4242EJXUMA1). The receiver is a Texas Instruments' chip, OPT101, which has a photodiode of dimension 2.29 mm $\times$ 2.29 mm in the center along with amplifier circuit with an internal gain of 1M V/V. The gain was increased 10x by adding a 10 M ohms resistor along with a 5pF capacitor. The output was buffered and given an additional gain of 10x using a general purpose opamp (ADA4177), making the total gain of the circuit 100 M V/V (80db).

The four-layer PCB design was 12 mm $\times$ 80 mm and dependent on the geometry of the wand. The PCB included a 5 V regulator (STMicroelectronics's L78L05) and a negative voltage converter (TI's TL7660CP) (Fig.3(c)). A 9 V Li-ion battery was used to power the whole board and was placed in the back of the device. The LED control lines and photodetector's amplified voltage output were connected to an Arduino' AtMega 2560 placed outside the enclosure. The microcontroller was connected to the laptop via USB to collect data and the analysis was done offline.

B. Software Design

Arduino's two digital output pins were used to control LED pulses. 405 and 470 nm LEDs were turned on for 1 ms alternatively. The built-in 10-bit Arduino's analog-to-digital converter (ADC) with a 5 V was triggered each time a source went high, and a reading was taken after the source output stabilized. An additional background measurement was made immediately after turning off both the LEDs and reading the ADC value in each cycle. This background measurement was subtracted out as the ambient light measurement from the other two readings.

IV. VALIDATION & RESULT

A laboratory setup was used to characterize our device and measure its sensitivity to pH change. The device was tested with FL in different buffer solutions to simulate the

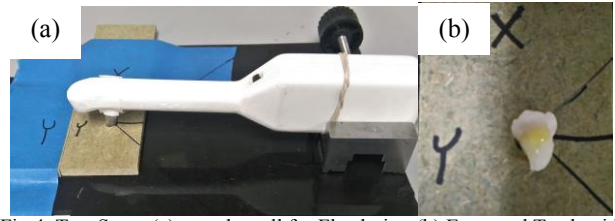


Fig 4. Test Setup (a) sample well for FL solution (b) Extracted Teeth with FL solution

change in pH due to plaque and food. The pH in each case was tracked using the ratio of the fluorescence stimulated by the 470 and 405 nm LEDs, adjusted for device noise and background noise. The device was then tested using fresh human plaque mixed in sugar solutions and FL. As a control, we tested the FL in different buffers and FL in a plaque solution for photobleaching. Two FL buffers were tested on teeth to assess how viewing angle and distance affect the fluorescence ratio.

1) pH Sensitivity

Four phosphate buffer solutions (PBS) of different pH strengths (7.17, 5.86, 4.72 and 3.82) were prepared. 200 μ L of each pH solution was mixed with 20 μ L of 0.4 millimolar of FL. 100 μ L of the resulting solution was transferred to a sample well as shown in Fig. 4(a). DpOW was fixed at 1 cm from the tray. An average of 60 readings per minute were taken for 10 min in a dark room as shown in Fig. 4(b). The mean emission ratio over 10 min at each pH is plotted in Fig. 5(a) with the standard errors. The detector has standard error of 0.064 at pH 7.12, 0.0112 at pH 5.86, 0.0019 at pH 4.72 and 0.004 at pH 3.82 with a 0.94 correlation coefficient for linear regression. Fig. 5(b) shows the emission ratio against time for each pH.

2) Sugar Induced Acidification

Fresh plaque was scraped from teeth using a dental pick and was centrifuged with 400 μ L of PBS (pH 7.12). The extra buffer was taken out and the plaque was mixed with 400 μ L of distilled water and 30 μ L of 0.4 millimolar FL solution. The pH of the sample was measured using a standard pH meter (Thermo Scientific Orion Star A211 Benchtop Meter). Then, 100 μ L of the solution was added to the sample well (Fig 4(a)) with 20 μ L of 0.1M sucrose solution. The DpOW data was recorded for 20 mins with a 1 min interval in a lighted room. Afterwards, the sample was transferred back into the solution tray and its pH was

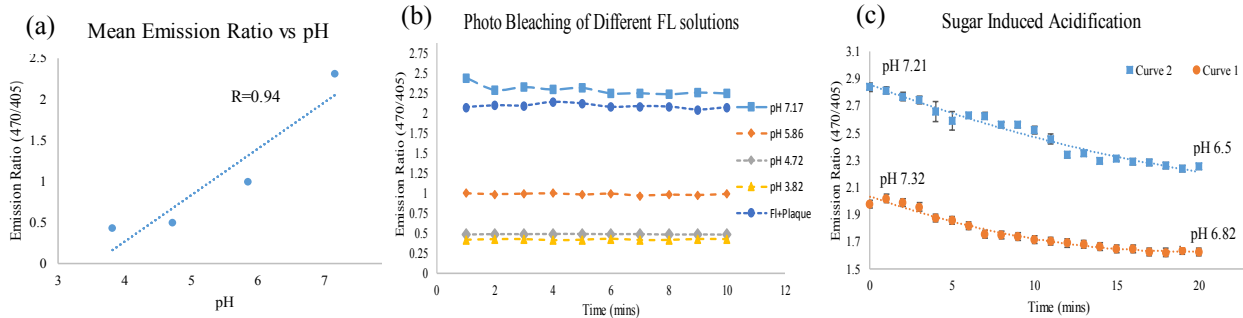


Fig. 5. (a) pH measurement using the device with fluorescein in different buffer solutions (b) Photobleaching of fluorescein (FL) solutions (c) Sugar induced change in the emission ratio (470/405) using fresh plaque, fluorescein and sugar

measured using the benchtop pH meter. The entire process was repeated on another day. **Fig. 5(c)** shows the two pH response curves, one with a drop-in plaque pH from 7.32 to 6.82 and another with a drop from 7.21 to 6.5 over 20 min. All measurements in **Fig 5(c)** are averaged over 45 repeated measures. The standard errors in Curve 1 are between 0.03 and 0.01, while those in Curve 2 are between 0.08 and 0.01. Recovery to the initial resting pH is not observed due to the absence of circulating saliva.

3) Dental Autofluorescence

pH 7 and 4 FL solutions were tested on teeth with Opti-Wand above at 0 and 2 cm (**Fig 4(b)**). The emission ratio was also noted for different angles varying from -30° - 30° , keeping the distance constant at 1 cm. At a distance of 2 cm, the FL emission ratio decreased 30% for a solution with a pH of 7 and 10% for a solution with a pH of 4. The angle dependence of the ratio for pH 7 varied between 14% and 6%, and between 13% and 5% for pH 4.

V. DISCUSSION & CONCLUSION

The ratio of fluorescence emissions at the two excitation wavelengths, 470 and 405 nm, was used as a parameter to track pH. For the buffers, 470 nm excitation produced a pH-dependent emission while the 405 nm emission channel remained constant at a low emission value due to weak FL absorption at 405 nm. In the presence of a dental surface, this channel has a higher value due to the teeth's AF and may serve as a reference channel. The Opti-Wand can track the decrease in FL emission but has a steep slope in the pH range between 7.12 and 5.86. The slope approaches zero for values between 4.72 and 3.82. The device needs a reduced noise floor to increase sensitivity for quantitative measurements below pH 5. The device works best at a distance up to 1 cm from the dental surface. The fluorescence ratio drops by 30% at 2 cm away from teeth as a result of the diminished AF signal received by the photodetector. Redesigning Opti-Wand to a coaxial fluorescence illumination-detection design is expected to reduce this distance dependence (**Fig. 3(a)**). The angle variability can be further improved by using a weighted ratio depending on the intensity profiles of the teeth's AF and FL's emission. **Fig. 5(b)** show that FL emission remains constant for a given pH over 10 mins (< 1 min excitation), demonstrating negligible FL photobleaching; this fact has been supported in a recent study using FL and rhodamine B [11]. Our study and prior work both demonstrate that FL is sensitive to plaque pH changes with sugar exposure, but only our study tracks pH change using a wand and single non-toxic dye for rapid clinical translation. Higher pH FL is more sensitive to photobleaching than lower pH but also has a steeper emission change with pH. The sugar induced acidification curve in **Fig. 5(c)** shows the drop in pH of a FL-Plaque solution after glucose intake on two different days. The curve exhibits a slower drop than the standard Stephan curve which may arise from using plaque in an external medium. In vivo testing would be able to further validate the device.

Although this is the first noncontact oral biofilm pH Opti-Wand, there are limitations to this 1st-generation device. The device is designed to measure relative pH change, not absolute values. Nonetheless, the device can be used to rank different locations in the mouth in regard to pH, which will enable dentists to consider another risk factor prior to the application of preventive therapies. Also, the device can be calibrated using pH strips in interproximal regions; however, the non-linear characteristic of the device will pose difficulty in absolute measurements. Nonetheless, this device has demonstrated the feasibility of an oral pH measurement tool. Improvements to the Opti-Wand will extend its pH measurement range, increase its sensitivity to distance/orientation, and lower the required dye concentrations. Future developments will likely require imaging capabilities since dentists are still quite visual in their diagnosis of caries. An image-based user interface would provide a "heat map" of dental pH.

In conclusion, the Opti-Wand was designed to be a non-contact, quantitative dental acidity measurement device. We plan to test the device in a dental clinic to obtain user feedback and data to refine the packaging and pH algorithms. A low-cost DpOW device could be used in the clinic for informing patients regarding diet and dental hygiene. We hope that this device would eventually help dentists apply preventive therapies in their clinics, and an at-home version will give patients real-time feedback for dental hygiene and diet.

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