Advanced Project Report

Mahir Amer and M. Zirdi Syukur

June 24, 2021

1 The Big Idea

More decayed teeth are more transparent [5]. Known by the medical pathology ”caries,” cavities can occur when decay causing bacteria start slowly de-mineralizing tooth. It is difficult and expensive to treat, and general consensus is that early detection allows for the best prognosis. We hoped to build a device that would measure this increased decay by means of how much more light is transmitted, a process called transillumination. Our objective was to also make the device consumer-friendly. While this sort of probing is already being done, the medical ”gold standard” is still to use X-rays - which poses a risk for radiation damage and limits how frequently and easily this can be done. We are proposing to use RGB LED light to avoid this risk to damage, and make it consumer friendly. We are testing whether RGB wavelengths (455-625nm) are capable of transilluminating a tooth to detect caries.

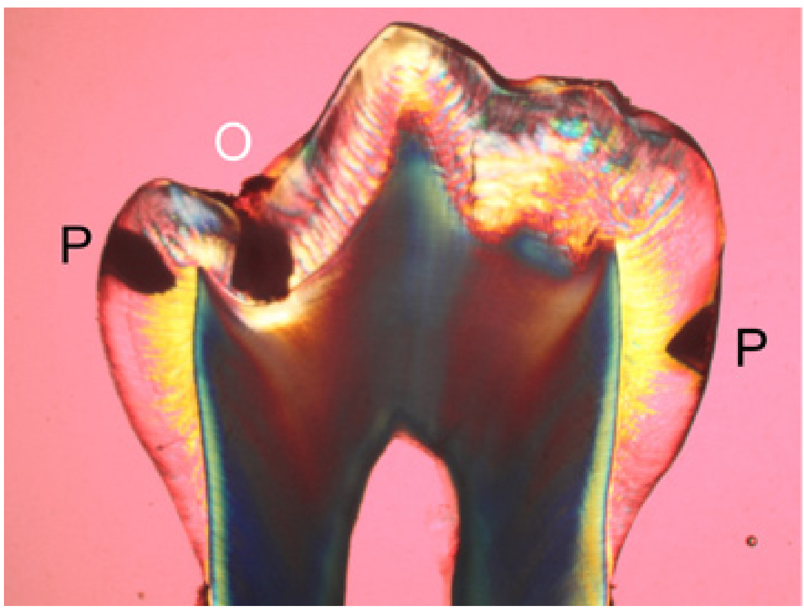


Figure 1: Carries diagram, lifted from Fried article [1]. Displays a section of a premolar tooth with several carries. Annotated in O and P and colored black are occlusal and inter-proximal carries. There is also a visible difference between the dentin layer (inside) and the enamel layer (outside) of the tooth.

2 The design

Keeping with our goal of making the device consumer-friendly, we aimed to model the device after an electric tooth brush. Constraints of our design were:

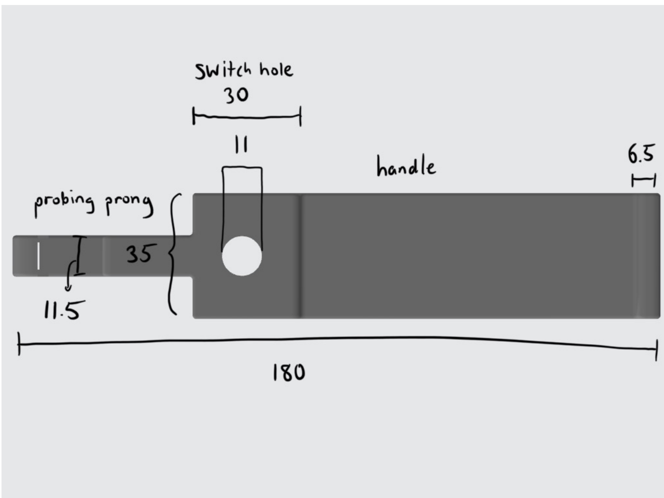
1. It had to be as light as a tooth brush for easy use.
2. It had to be able to carry the power source for the device, an RGB LED, a photo-diode, a switch and necessary circuitry.
3. Components and whole device should be cheap in order to make it accessible to many people.

4. The portion of the device that will be inside the mouth - the probing part - will need to be sealed well enough that it can be washed without spoiling the underlying electronics.

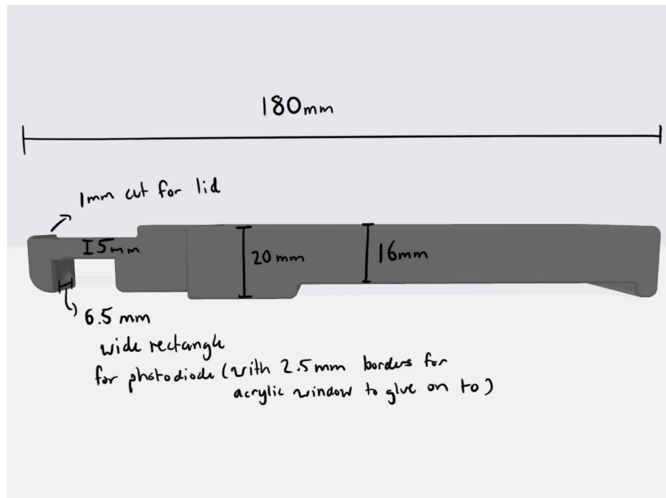
5. The probing part will also have to be small enough to not be restricted by the curvature of the mouth.

Additionally, we considered logistical factors like: printing time (given the time constraints of the project) and the specifications of the printer itself. In our case both our prints took nearly a day to print, wash, cure and sand. We also had to modify the design slightly so that the printer could actually house it.

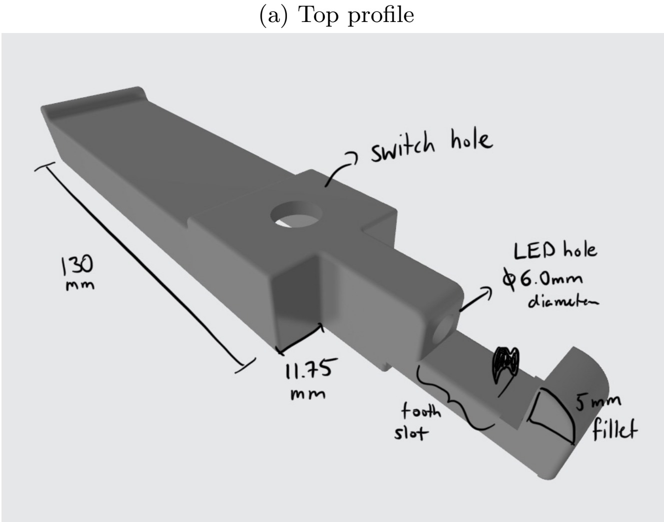
2.1 Schematic



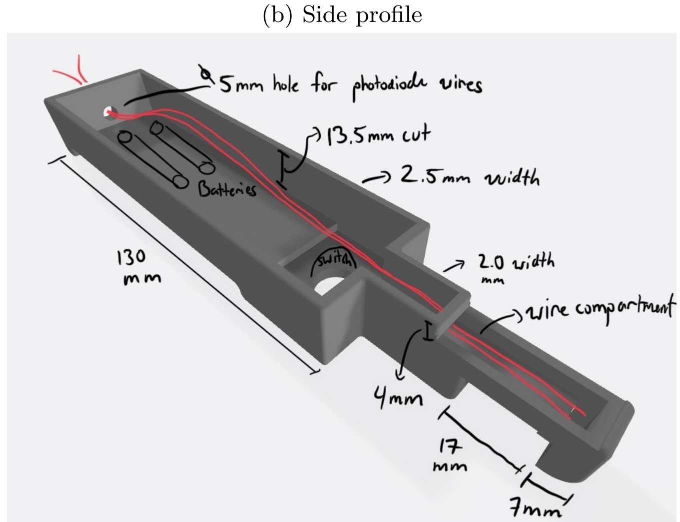
(a) Top profile



(b) Side profile



(c) Top view from an angle



(d) Bottom cavity from an angle

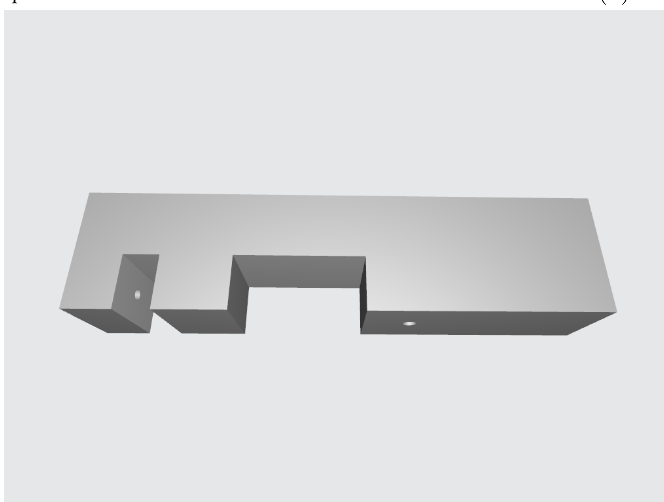
Figure 2: Here is the rendered STL file of the current device. This schematic does not contain all dimensions of the device but details the important ones. The take away from these dimensions is that they were made to be as small as possible without compromising structural integrity and comfortability. All measurements are reported in mm.

2.2 Describe the design process, including prototypes you abandoned.

The design process involved measuring our components first and assessing what the form factor would be to fit all of them in. We also had to approximate measurements for oral palettes so that the device could probe specific tooth whilst not being uncomfortable for the user.

(a) Top profile

(b) Side profile



(c) Top view from an angle

Figure 3: Prototype 1: A Giant's toothbrush. It was 220 mm in length and the "prong" to bite over was 50 mm tall (making it impossible to use). Additionally, the holes made were too small to fit the components.

The first prototype was largely an over-estimate in almost all respects. While we were able to fit all necessary components, the device was unfit for the oral cavity. A major reason for this over estimate was the uncertainty about the structural integrity of the material for the print. Upon redesign, we deducted the thickness on all but a few walls of the device by 50 percent leading to a significant size reduction. We also made the probing part of the device much smaller. The redesign also involved a different material. While prototype 1 used PLA Filament from a FDM (extruding) 3D printer, prototype 2 used resin from a stereo-lithography 3D printer. This second type of 3D printing was more desirable because it had a more precise resolution (25 micrometers). As we were making our design as small as possible, having such precision was necessary.

3 The construction

3.1 A table with all your materials, including the source and the cost

Material list

1. x1 3D printed mount (self designed as stated above)
2. x1 RGB LED $1.28 (source link: shopee)
3. x1 Photodiode $1.27 (source link: digikey)

4. x1 AAA Battery Holder, estimated price: $1.93 (original source link: lazada however we winded up using a smaller AAA battery holder we borrowed from Ben's lab)

5. x1 four-way Switch $10.98 (source link: digikey, model A12315RNCQ)

6. x2 AAA Batteries (self sourced from Ben's lab, estimated price: $1.28)

7. x2 Acrylic laser cutted 9mmx9mm windows (sourced from YNC fab lab

Total cost: $16.74 for one device (not including 3D print costs/acrylic/voltmeter costs)

3.2 Circuitry

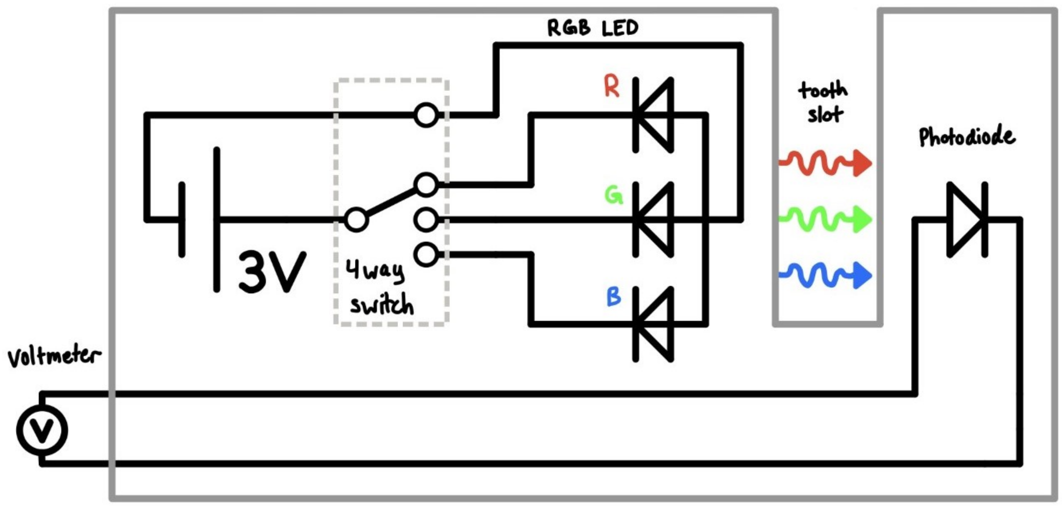
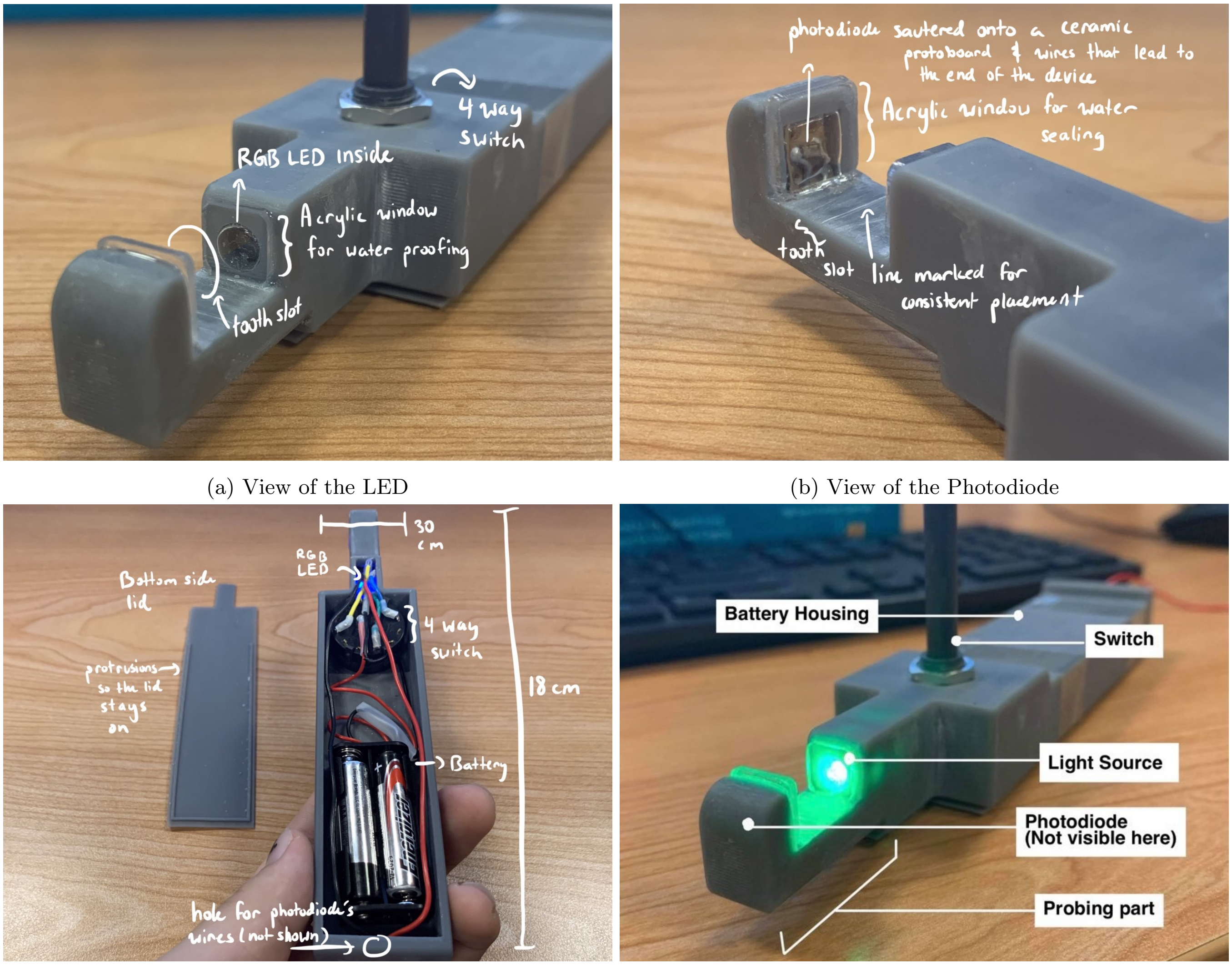


Figure 4: This is the circuit diagram of the device. Tested on a breadboard before installing onto the mount. 3V came from two triple A batteries. The ground terminal of the RGB LED was the longest and 2nd prong on it, which is not evident in the diagram.

3.3 An annotated picture of the completed device

After procuring all the materials and the 3D prints, we started assembling. It should be noted that after printing corners were rounded and surfaces were sanded to enhance usability. Additionally a circular groove had to carved on the inside of the 4 way switch housing that is adjacent to the switch hole. This hole was so that a prong on the switch could be fixated to a small hole. This is present so that the switch is locked into place. The circuitry was first tested on a bread board before final soldering. We also made sure to include shrink wrap around soldered wires to prevent short circuits. Some components like the switch were screwed in and others were glued using two-part epoxy. The back lid was taped on because it's design wasn't perfect (and the print of it failed due to its thinness). We did not have time to perfect the design of it.



(a) View of the LED

(b) View of the Photodiode

(c) View of the opened up backside

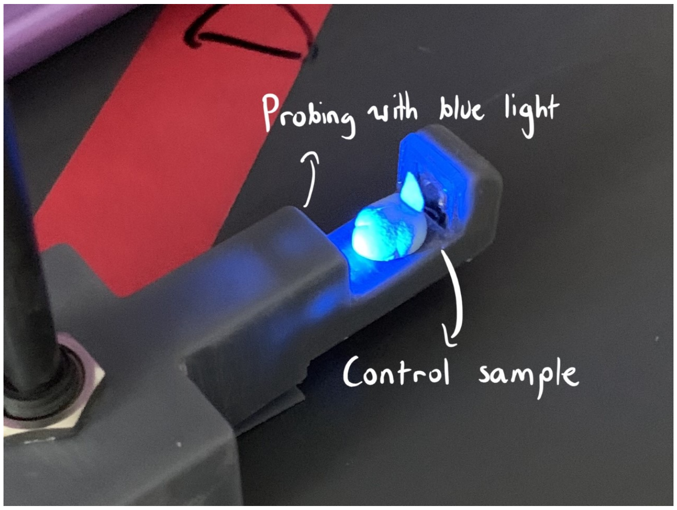
(d) View of whole device

Figure 5: Completed Device

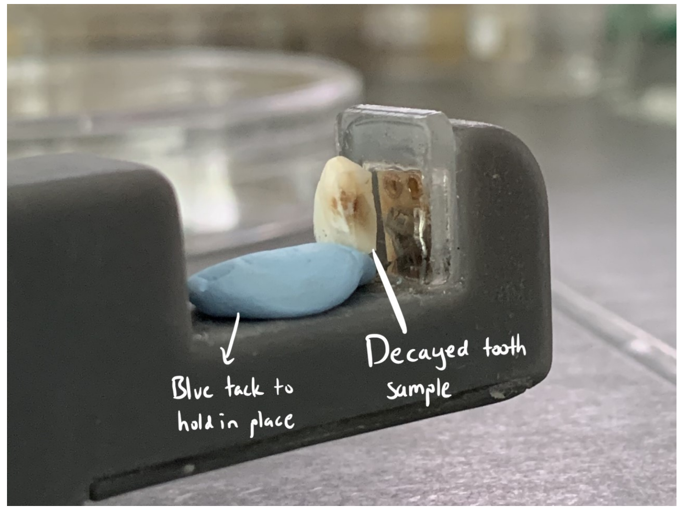
4 The data

4.1 Data Collection Methodology, Probing with test teeth samples before proposed human testing

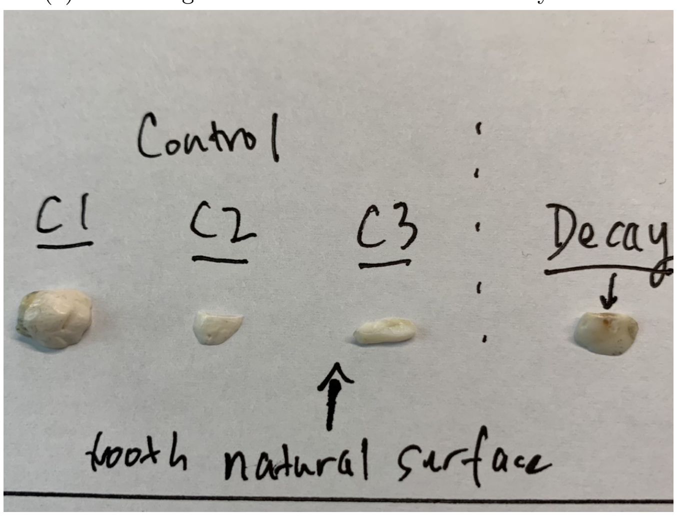
1. Prepare thin slices of teeth, some with decay and some healthy control teeth
2. Place the device in a dark isolated environment (we used an ice cooler) with no teeth and with the RGB LED turned off.
3. Connect the wires at the back of the device to a voltmeter, and note the voltage generated on the photo-diode.
4. With each color of the RGB LED now on, repeat step 3 three times. This is a measurement of the incident light.
5. Take the device and place a teeth slice in between RGB LED and photo diode in a pre-etched marking. Ensure that the natural tooth surface faces the LED, is placed roughly the same distance from the diode, and the device is placed under the same dark conditions and location in the ice cooler as the previous measurements.
6. Repeat step 4 but this time with the samples in between the LED and the photo-diode to measure transmitted light.
7. Do above with all teeth samples.



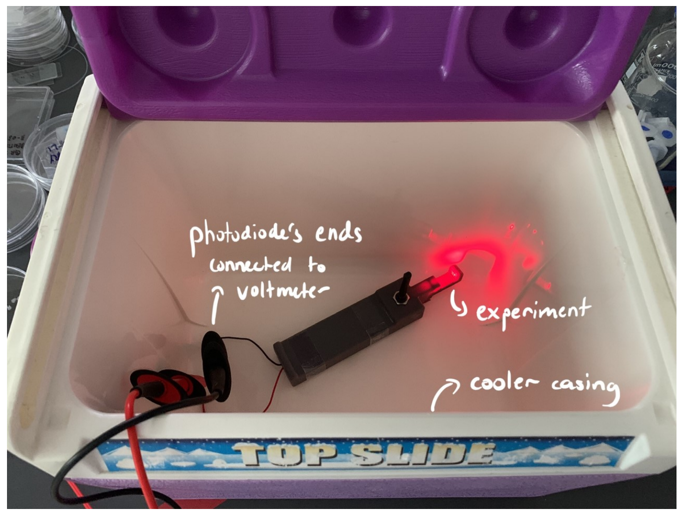
(a) Measuring transillumination with a healthy control



(b) Prepping decayed tooth for measurement



(c) All tooth samples. Control 1 and Decayed tooth are part of the same tooth.



(d) Setting up the device for the experiment in an ice-cooler

Figure 6: Completed Device experimentation

4.2 Measurements and Data Processing

Sample	No Light	Red	Green	Blue
No tooth	5.8	301.1	258.8	240.6
Decay run 1	NA	188.8, 188.2, 188.0	45.1, 44.8, 44.7	23.7, 23.9, 23.7
Decay run 2	5.5, 5.7, 6	233.9, 234.5, 234.4	128.2, 129.0, 129.3	52.3, 51.2, 52.2
Control #1	4.1, 4.3, 4.9	213.7, 213.8, 213.8	63.2, 63.5, 63.6	23.0, 23.1, 23.3
Control #2	5.5, 5.3, 5.3	228.1, 227.9, 227.8	119.3, 119.4, 119.5	56.5, 56.7, 58.0
Control #3	63, 6.2, 6.3	223.2, 223.6, 223.5	118.6, 119.0, 118.7	57.8, 58.0, 58.4

Table 1: Raw data table. All following measurements are in mV (millivolts). The uncertainty in each measurement is 1.47 mV (see uncertainty section). There are three trials per per cell. Decay run 1 was scrapped from data processing because we forgot to take a baseline No Light measurement and the conditions under which they were done were different from the rest of the experiment.

Measurements were taken by placing the tooth as shown in Figure 5(b). A piece of blue-tac was first placed to 1. hold the tooth in place and 2. to standardize the distance of the tooth from the light source. The blue-tac had to be sturdy enough to offer support but small enough so that it did not block any light or elevate the tooth beyond the photo-diode. It is important to note that Control 1 and the decayed tooth sample were part of the same tooth and control 2 and 3 come from two other samples of healthy teeth.

Thickness of Teeth	Control 1	Control 2	Control 3	Decay
[cm] ± 0.0001	0.0398	0.0175	0.0171	0.0257

Table 2: Thicknesses of different samples of teeth , measured from the tooth's natural surface to its longest width perpendicular to it.

We also needed to measure the thickness of the samples as the length of the light path influences in how much is absorbed or transmitted. The "natural length" of the tooth - meaning the thickness of the tooth when it is propped up - was measured separately using a micrometer and measurement uncertainty is estimated to be 1 micrometer.

4.3 Results

We processed the data by first subtracting the "no light" voltage measurements from the rest of the measurements. Then we calculated the attenuation coefficient of the teeth samples. This quantity tells us how much light is transmitted per unit centimeter. This was the appropriate metric to compute/compare because it normalized our measurements by how thick each tooth was. A tooth with a high attenuation coefficient means it is less transparent compared to a tooth with a lower attenuation coefficient. Comparison for different wavelengths of light for the same tooth also reveal which wavelength of light is most absorbed. The data is processed into a table below and then plotted into a spectrum

The following formula was used to convert the voltage measurements to attenuation coefficients:

$$\mu = \frac{-ln\frac{I}{I_o}}{x} \tag{1}$$

We took the ratio of two voltage's emitted by the photo-diode: voltage of transilluminted light (through teeth) and the voltage of incident light (what we measure without teeth). The ratio of these two is equivalent to I/I_o as the Intensity of light and voltage produced by the photo diode are proportional such that their ratio is the same. x is the length of a tooth which has been measured in table 2.

	Control 1	Control 2	Control3	Decay
Red	9 ± 2	16 ± 3	18 ± 3	10 ± 3
Green	36.6 ± 0.3	45.5 ± 0.5	47.3 ± 0.4	28.1 ± 0.5
Blue	63.6 ± 0.9	86.5 ± 0.7	88.4 ± 0.7	63.3 ± 0.7

Table 3: Processed data of Attenuation Coefficients, all data in this table is in units of per centimeter

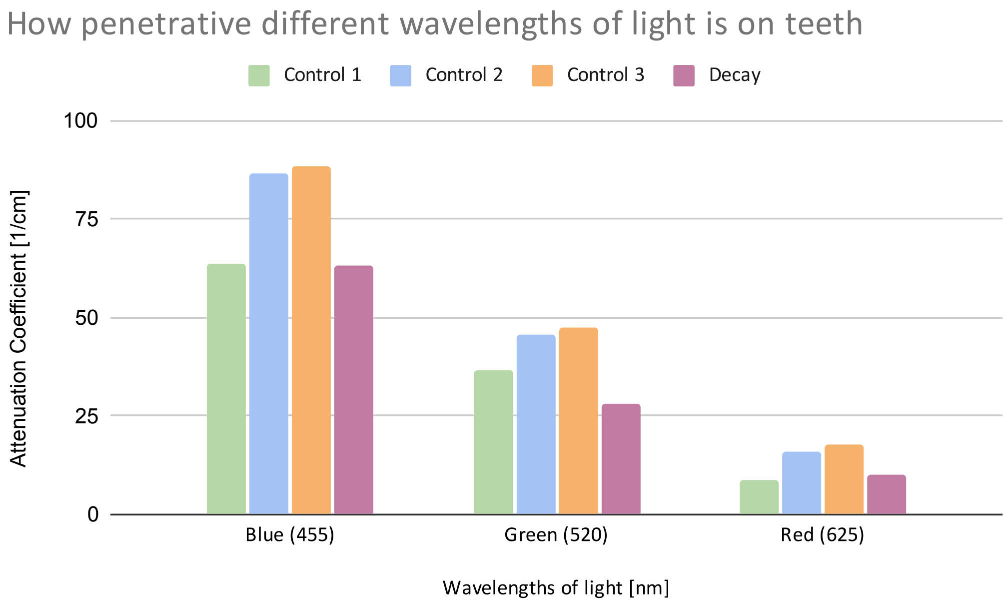


Figure 7: Plotting an Attenuation Coefficients spectrum for different teeth samples. Data was plotted in bar graph format to put different channels for RGB. It was also represented this way because our experiment did not have enough datapoints to have a boxplot. However, the propagated uncertainties were so small relative to the value that the they would not be noticeable on the bar plot nor the boxplot. The wavelengths of the RGB channels of the LED are taken from a data sheet of a similar RGB LED common anode as the exact data sheet of our LED was not provided by the vendor.

We compared our results with the data from Figure 3 of [2].

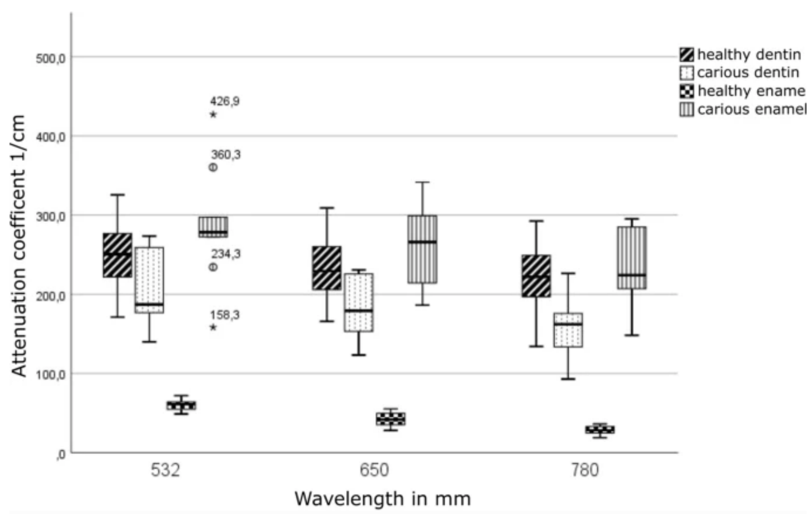


Figure 8: Reference values from Figure 3 of Hoffmann, L., Feraric, M., Hoster, E. et al [2]

It seems that the values we found in our experiment do not align with the literature values. And the uncertainties in our experiment are small enough to say it is distinct from those measurements (Because the uncertainty in our experiment is low and has a limit of quantification much smaller than the marginal difference). It does seem, however, that our measurements follow the same trend in the literature values, in that longer wavelengths (red) have lower attenuation coefficients, which is, they transilluminate teeth more as shown by the healthy enamel measurements from literature. We would also suspect that our measurements may show slight evidence for decay having decreased attenuation coefficients as while control 2 and 3 are consistent with one another, the measurement of decay sample's attenuation coefficients goes down. I say this without regards to control 1 because we think that there is potentially some error involved with control 1 as it did not align with the other two controls and that it was actually sourced from the same tooth as the decayed sample. So control 1 may have some underlying decay already in it. For these reasons, we would conclude that, although our measurements are consistent and precise, there is likely some large systematic error that separates it from the literature values. This experiment would also reaffirm other literature that state the limited transillumination potential for RGB wavelengths. According to the Fried article [1] low energy transillumination of teeth is limited. As within the visible spectrum it is burdened by random light scattering inside the tooth, and this effect gets more severe with shorter wavelengths. On the other hand, wavelengths of light greater than 1400 nm get absorbed by water. Literature, would then suggests using light around 1300 nm as it is when light scattering and water absorption is minimum. Perhaps in this experiment, the limiting factor is the random light scattering inside the tooth due to the wavelength of light. Such a consequence could also explain the trend that we measured, in how longer wavelengths (red) was attenuated by the tooth much more strongly.

4.4 Write about the signal, sources of noise, systematic uncertainties, etc.

One of the sources for uncertainty was the position of the device inside the box as shown in Figure 5(d). The box was used to isolate ambient lighting. However, the box had its own reflectivity, which seemed to have influenced our readings.

Red light	Trial 1	Trial 2	Trial 3
Corner	234.0	233.9	233.8
Center	231.1	230.9	230.89

Table 4: Testing the box interference. All data in this table is in units of millivolts

By taking the mean value across trials and finding half of the range between eh corner and center measurements. We determined that this source of uncertainty amounts to roughly ± 1.47. This is the uncertainty that we chose to represent all the voltage measurements (as it was higher than most values of variation across trials). All uncertainties reported are propagated from this value.

There is perhaps a large systematic error preventing our experiment to agreeing to literature values. For example. The literature had separated teeth into health dentin, carious dentin, healthy, enamel, and carious enamel. Where we simple had separated carious teeth from health teeth. Literature seems to suggest that the effect caries have on the attenuation of these two different parts of the teeth have different effects. Since we could not separate them in our sample, they may have influenced each other. Additionally, the literature used teeth samples of consistent length where our samples were more like chipped fragments with varying lengths.

Lastly we also suspect that perhaps there is more, non transmitted light, sneaking through our experiment. An example was illustrated above with the reflection of the ice cooler, however more light could have slipped through the teeth by going around the sample, or reflecting off of the device. When conducting preliminary tests with the mouth, which yielded similar results, the light could have slipped in between the teeth and did not represent transmitted light, but incident light.

5 The future

5.1 What are the next steps to improve your design or update your instrument?

A reduction in the size of the light source is a crucial requirement as the current setup causes too much light to leak around the tooth. In addition, currently, we can only really probe the front teeth. In order to probe teeth that are deeper into the mouth, such as molars, the probing part will have to be even more streamlined. Research suggests maximal transmission occurs at 1310-1550 nm, [3] Reflectance may also be a method to consider, and might be easier to design considering the light source and the detector will be on the same side of the tip, although, this too would likely require further reconsideration into the wavelength of LED chosen [6].

In real world usage, we may have to take some more measurements in order to control for the dryness, or lack thereof, of teeth. During our experiment, we had the advantage of probing dried samples. Although, literature seem to suggest that this won't be an issue unless we venture into wavelengths greater than 1400nm.

During the project, data collection was done through a voltmeter, which is clearly not a consumer-friendly addition. Instead, we could house a wireless modem onto the device that will connect with a phone, where data will be analyzed real-time to tell the user whether their teeth are too transparent or not. Such additions would increase the price of the device but benefit the long-term goal of user friendliness.

The switch may also be redesigned so that it is not just a road that your spin but some kind of 3D printed lever or knob. We did not have time to design and print this part. The same goes for the backside lid, which though was redesigned to be thicker, did not have the time to be printed (as 3D Printing takes a long time!)

There is reason to believe that even in the visible range, light can be damaging to teeth. And while this damage is less than what is caused by X-rays, it is still something to keep in mind.

5.2 Are your goals for this instrument feasible to achieve?

Yes, in the sense that the market for non x-ray, consumer friendly probing device is there. There are devices like "DIAGNOdent™," which have a similar goal of making a consumer friendly portable probing device, but use laser induced fluorescence instead."[4]. This devie is considered "a valuable adjunct to clinical examination." It makes use of long pass filters to restrict the wavelengths being received and the use of a much finer probing tip that contains the light source and the detector in the same module. If we reconsider the wavelengths of light, evaluate sytematic errors such as the size of the light source, and potentially consider the reflectance mode, this device does have "medical potential," according to Prof HSU.

6 Credits and Thanks

Ben Olsen - Assistant Professor, Yale-NUS College Physical Science Department, Stephen HSU Chin-Ying, PhD - Associate Professor, NUS Faculty of Dentistry, and Guang Rong TAN, PhD - Research Fellow at NUS,

7 Location

This device was built at the Yale-NUS Science Center and the experiments were conducted at the National University of Singapore's Center for Oral Health.

References

[1] Daniel Fried. *Detecting Dental Decay with Infrared Light Kernel Description.* 2020. URL: https://www.osa-opn.org/home/articles/volume_31/may_2020/features/detecting_dental_decay_with_infrared_light/.

[2] Lea Hoffmann et al. "Investigations of the optical properties of enamel and dentin for early caries detection". In: *Clinical Oral Investigations* 25 (Mar. 2021). DOI: 10.1007/s00784-020-03434-x.

[3] Robert Lee et al. "Nondestructive assessment of the severity of occlusal caries lesions with near-infrared imaging at 1310 nm". In: *Journal of biomedical optics* 15 (July 2010), p. 047011. DOI: 10.1117/1.3475959.

[4] Adrian Lussi, Raimund Hibst, and R Paulus. "DIAGNOdent: An optical method for caries detection". In: *Journal of dental research* 83 Spec No C (Feb. 2004), pp. C80–3. DOI: 10.1177/154405910408301S16.

[5] María Melo et al. "Combined Near-Infrared Light Transillumination and Direct Digital Radiography Increases Diagnostic In Approximal Caries". In: *Scientific Reports* 9 (Oct. 2019). DOI: 10.1038/s41598-019-50850-5.

[6] Jacob Simon et al. "Near-IR transillumination and reflectance imaging at 1,300 nm and 1,500-1,700 nm for in vivo caries detection". In: *Lasers in surgery and medicine* 48 (July 2016). DOI: 10.1002/lsm.22549.