FINAL REPORT: THE BEND-AID

A Non-Invasive Intracranial Pressure (ICP)
Monitoring Device

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by Team All You Need Is Lobe

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1 Executive Summary

Background

Intracranial Pressure (ICP) is a measure of the pressure in the brain. If left untreated, high ICP levels can cause seizures, decreased cognitive functioning, and even death. Doctors use two main techniques to measure ICP in infant patients: ventriculostomy- a highly invasive procedure that requires drilling into the skull - and fontanelle palpation, where doctors palpate the anterior fontanelle to qualitatively assess ICP. These procedures present significant drawbacks. Due to this, we wanted to develop a novel technology that is able to measure ICP in infant patients both accurately and noninvasively.

2 Market Analysis

We performed research on the financial metrics of existing industries that align with our product. To that end, the market analysis covers both different medical professionals as well as potential patients. It can be seen in the table below.

Table 1: United States Market Size for Intracranial Pressure Monitoring Device

Market Segment	**Estimated Market Size (US)**	**Competitive Products and Solutions**	**Willingness to Pay**	**TAM**	**References and Reasoning**
Neurosurgeons	5,343	Ventriculostomy, microtransducer devices	<$1,500 (average cost of ICP measurement procedure)	$921,667,500	Assume an average patient panel of 2,300 patients, assume 5% get tested.
Pediatricians	57,491	Tympanic membrane displacement, optic nerve sheath diameter, MRI/CT	<$200 (cost of inner eye exam)	$264,458,600	Assume an average patient panel of 2,300 patients, assume 1% get tested.
General practitioners	111,127	Tympanic membrane displacement, optic nerve sheath diameter, MRI/CT	<$200 (cost of inner eye exam)	$511,184,200	Assume an average patient panel of 2,300 patients, assume 1% get tested.
ER doctors	39,547	Ideally less invasive methods, but ventriculostomy in worst cases as drainage or temporary skull removal to relieve pressure may be needed	<$400 (average of costs between non-invasive and invasive techniques)	$24,595,905	Assume 1% of total ER patients in the U.S. (4,919,181 patients) get tested [**?**].

Design Strategy

Adopting the 7-step iterative engineering design process, we first conducted a thorough literature review of currently existing technologies to identify industry benchmarks and deficiencies. This allowed us to better understand the market needs. We used this to develop several specifications for our product that would uphold its quality, as described below. Next, we brainstormed potential solutions that addressed the most pressing needs we found from our literature review. Through multiple stages of prototyping, our solution gradually achieved all the desired functions, including measuring ICP in a non-invasive and accurate way. We also added calibration, alert system and data storage to capture ease of use. Our final solution is consisted of an attachment for securing the sensor on the patient, a hardware circuitry on a printed circuit board and a software program written in C++. The process will be described in detail in **Section 4 Design Strategy**.

Design Criteria

We defined a set of criteria to ensure that the product was an improvement over current methods. With these criteria in mind, we aimed to design a solution that was:

1. Noninvasive
2. Accurate for clinical use
3. Relatively continuous
4. Clinically viable for several days
5. Easy to set up
6. Inexpensive

Project Status

Our device has passed all the tests we designed for the specifications, thereby meeting all the defined design specifications. Human testing is pending IRB approval. Limited by time, we were not able to realize all the potential improvements we wish to add onto our design solution, including updating the printed circuit board, modifying the modular code to fit sensors of different sizes, adding user interface and incorporating our device with the bedside monitor in use in clinics.

3 Introduction

Infants suffer greatly from neurological complications such as traumatic brain injuries (TBI) and hydrocephalus. One of the main indicators of such diseases is high intracranial pressure. High ICP causes swelling of the brain tissue and the ventricles. This causes a myriad of biological consequences if left untreated [1]. Monitoring and treating high ICP is paramount to delivering quality patient care.

There are two main ways of monitoring high ICP in a clinical setting, and each of these has drawbacks [2]. The gold standard of ICP monitoring is ventriculostomy. Neurosurgeons drill a hole in the skull and place a sensor in the ventricular region of the brain. This provides highly accurate pressure readings. However, the invasiveness of the procedure makes it less than ideal. It is expensive, poses a risk for bacterial infection, and presents cosmetic challenges due to tissue scarring. The physical toll it places on a patient, let alone an infant, is extreme and mandates lengthy recovery [2]. An alternative technique that is far less invasive is fontanelle palpation. Fontanelles are soft spots in the skull that protect the infant cranium during its early development. They typically close up after 18 months. Here, doctors palpate the anterior fontanelle to qualitatively assess ICP. The results are highly subjective and vary greatly between different healthcare providers [3]. As such, this technique is not fit to be used when making critical decisions regarding patient care.

Despite the effort devoted in revolutionizing the ICP monitor, existing solutions are not sufficient to fill the gap in the market, where an accurate and non-invasive method for monitoring ICP in infant populations is in need. Through the market analysis, we identified a total addressable market of 264 million dollars with pediatricians as major users of our device. Additionally, we noted needs from customers, purchasers and regulatory standards. Concluding all the needs, our design solution is desired to be safe, non-invasive, accurate and cost-effective, while meeting all relevant regulations and standards.

This report, therefore, provides a summary of the strategy we adopted in designing and constructing **Bend-Aid** - a novel, non-invasive, quantitative and accurate ICP monitoring device and all of related technical details, testings and recommendations for future work.

4 Design Strategy

To tackle the design challenge, our team chose to follow the engineering design process shown in **Figure 1**. Specifically, the team carried out thorough research to understand the inadequacies of existing solutions, such as the level of invasiveness in ventriculostomy and the user-dependence in fontanelle palpation methods. Based on the information gathered and the regulations surrounding the implementation of a design solution, the team defined seven design specifications which capture low invasiveness, accuracy, efficiency, cost-effectiveness and other desired features.

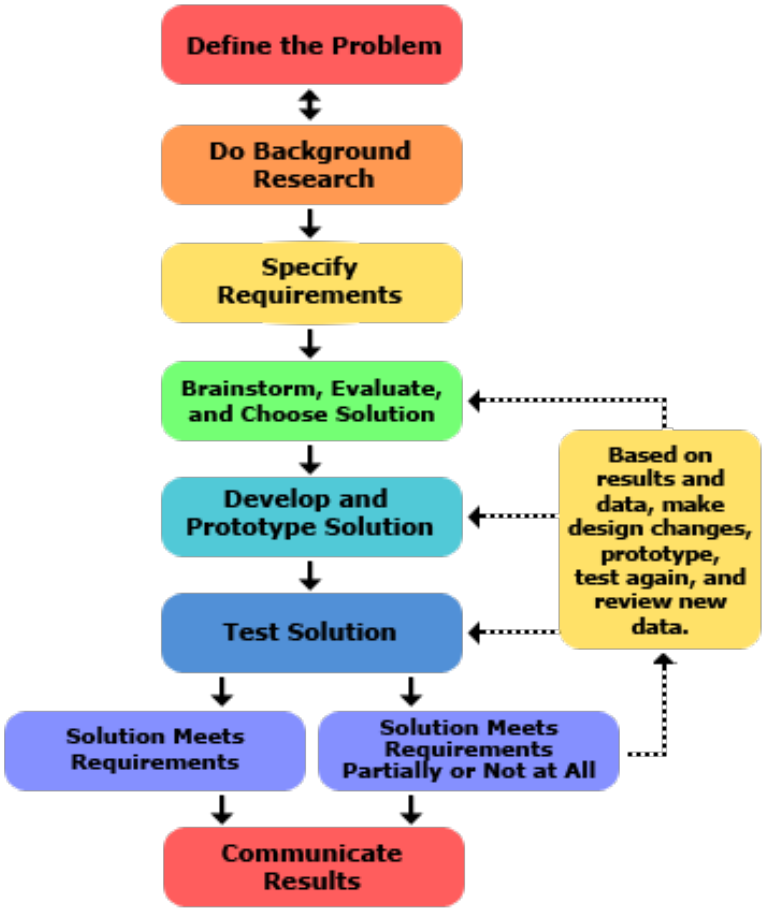

Figure 1: Engineering Design Process.

We then carried out two stages of brainstorming. In the first stage, the team focused on examining the possible technologies that can be utilized for monitoring ICP while the second stage happened after determining infants below 18 months old to be the target patient group because of the lack of a non-invasive yet accurate solution for this population within the current market. The focus of the second stage of brainstorming also shifted to the detailed functional components. At the end of each brainstorming stage, the team utilized Pugh Screening and Scoring matrices to evaluate the effectiveness of the possible design solutions against previously defined specifications. This way, an objectively better solution was finally chosen - to deduct ICP values from the level of flexion of the fontanelle using a flex sensor with varying resistance levels resulted from bending.

The solution, containing both hardware and software components, was prototyped in medium-high fidelity by December 2018 and contained more advanced functions to achieve higher accuracy level and user-friendliness by May 2019.

4.1 Design Specifications

To meet the needs of our customers, our team established the design specifications listed in **Table 2**. These design specifications take into account the needs of our customers which include the physicians/surgeons, the patients, and the hospital purchasing agents. These specifications also have measurable targets established by our literature research and client interviews that our chosen design solution must meet.

Table 2: Justification for Design Specification Target Values

Design Specification	**Target Value**	**Justification**
Measures ICP within ± 5 cm H_20 compared to ventriculostomy	± 5 cm H_20	Our clients stated that the ICP measurement should be within ± 5 cm H_20 compared to the existing ventriculostomy method [4].
Time Between Measurements	≤ 30 minutes	Our clients identified 30 minutes as the minimum amount of time between measurements for ICP measurements for high ICP to be detected before complications arise [4].
Time for operation	≤ 2 hours	The current method that our clients use, the ventriculostomy method, takes 20 minutes to 2 hours to complete. Thus, our solution's operation time should be equal to or less than the current method [4].
Total cost per use	≤ $1,500	Our clients currently measure ICP using the ventriculostomy method, and use single-use devices for this procedure costing $1,500 (Medtronic Ventricular Drainage Catheter + Camino OLM Intracranial Pressure Monitoring Kit + Display Monitor Equipment) [4].
Maximum time for monitoring (before risking complications)	< 6 days	There is an approximately 2.5x increase in the risk of cerebrospinal fluid (CSF) infections after the sixth day of catheterization [5]. The catheter in ventriculostomy is also usually removed within 6 days after surgery according to our clients [5].
Frequency of maintenance	Every 3 months	The current ICP monitor device being used by the clients (Camino ICP Monitor) has a recommended maintenance of once every three months [6].
Degree of invasiveness	No incisions or drilling	Our clients ideally want a device that is noninvasive for their patients. That is, it does not require surgical procedures involving incisions or drilling [4].

4.2 Problem Decomposition

Our design solution will consist of multiple functions and subfunctions, and we will consider each one separately during concept generation and screening. This will allow each aspect of our design solution to satisfy our design specifications. The six main functions of our device are user input, data acquisition, data processing, data transmission, data storage, and data display. These functions were divided into subfunctions as shown in **Figure 2**.

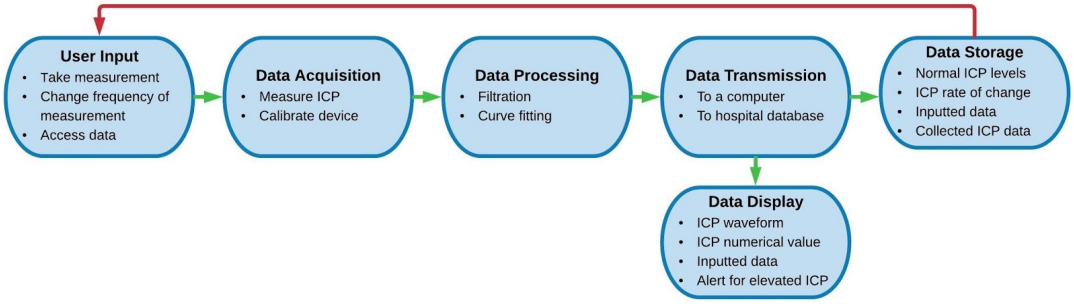

Figure 2: Flowchart of design solution functions and subfunctions.

4.2.1 User Input

Our design solution will include a mechanism with which a doctor or nurse can control data acquisition. This may include a method for the doctor or nurse to send a signal to the device to take measurements. If the device takes measurements continuously, the doctor or nurse would be able to change the frequency of measurements or to stop taking measurements altogether. The doctor or nurse will also be able to access ICP measurements at previous time points.

4.2.2 Data Acquisition

Following an input by a doctor or nurse to measure ICP, the device will acquire raw data to determine ICP. The data will likely be acquired through a sensor that measures a biological parameter that varies with ICP, such as CSF (cerebrospinal fluid) pressure, optic nerve sheath diameter, or blood flow velocity; the sensor will then send an electrical signal based on the biological parameter. Certain methods for acquiring raw data, such as directly measuring CSF pressure, may not be suitable for our design solution because of our design constraint of minimizing invasiveness.

If necessary, we may include a method for calibrating our device in order to confirm its accuracy and precision. We will determine possible methods for calibrating the device after selecting a method for acquiring the raw data.

4.2.3 Data Processing

The raw electrical signal will then be converted to a meaningful ICP measurement. Depending on the method for collecting the data, this may require multiple signal processing steps, such as filtration and curve fitting algorithms.

We will most likely incorporate one or more filters into our design solution. This includes both system noise filtration as well as frequency domain analysis to extract relevant frequency data. The necessary filtration methods required are dependent on the source of noise.

To convert the signals to a measure of ICP, we will likely use a curve fitting algorithm, such as linear, nonlinear, or multiple regression.

4.2.4 Data Transmission

Another functional component we have is data transmission, where the ICP data we obtained from previous steps will be sent to a system for storage and analysis. Based on the different systems the information is stored in, we have two sub-functions: transmission to a computer and transmission into the database of the hospital system. Possible options for achieving this goal desired would be through bluetooth, WiFi, and cloud sharing.

4.2.5 Data Storage

After receiving the data from the monitoring device, we will store the ICP data into the system. This is a very important function both for determining if the collected ICP levels from the patients are within a safe range and for the doctors and surgeons to later access the data for analysis. The four sub-functions include storage of normal ICP level, rate of change of ICP, inputed data, such as patient information, date and time, and collected ICP values. We imagine to integrate this function with existing storage method for Codman ICP monitor in use in Texas Children's Hospital, along with brainstormed ideas for alternative data storage method.

4.2.6 Data Display

For the users easily visualize and check the ICP data, the design solution will likely display real-time numerical ICP value, ICP waveform, and other patient's information. Similar to storing data, we would like this function to be integrated with the monitor currently in use so that it requires less training and lower cost for integrating the novel design solution. Therefore, brainstormed ideas will be based on existing monitors in Texas Children's Hospital.

It would be very valuable for our design solution to have an alert system which notifies doctors and surgeons of dangerous ICP levels. This would be achieved through two steps: comparing collected ICP levels to stored normal ICP level/normal ICP rate of change to make a binary decision between safe and dangerous ICP data and alarming to inform the doctors and physicians to take action for patients with abnormal ICP levels. We imagine to use integrated circuits with some electrical hardware to achieve this function, although the exact method is yet to be brainstormed after learning more about what Codman monitor uses.

4.3 Concept Generation and Screening

4.3.1 First Stage of Brainstorming

Our initial concept screening consisted of independent research (approximately five hours each) to generate initial ideas followed by a one hour brainstorming session where team members presented potential solutions. This session in turn inspired several additional novel ideas. After the meeting, the 79 different ideas were first separated into ideas for 1) patients below 18 months old, 2) patients above 18 months old, and 3) both age groups. In each group, the ideas are further categorized based on its nature and similarities with other ideas. The list of initial brainstormed solutions are in **Section 10 Appendix**.

4.3.2 Narrowing Down to Feasible Ideas

Each team member investigated two or more of the above categories in greater detail to determine the feasibility of each idea. The idea was deemed feasible if there had been previous work demonstrating a strong relationship to ICP from a peer-reviewed source or a theoretically possible proof of concept. During a second meeting, team members presented their findings, and discussed new ideas that came up during research. The following ideas were deemed feasible:

1. Electrodes [7]
2. Inject water soluble nanotubes into spinal space [8]
3. Poke finger/artery for flow velocity associate with ICP [9]
4. Shock patients and check recovery time - related to ICP [10]
5. Tympanic membrane IR sensor [11]
6. Measure pressure from vein/artery [12]
7. Laser diameter of major arterial (e.g. middle cerebral artery (MCA)) [13]
8. Halo test variation
9. Sonographic ONSD quantification [14]
10. Similar to dialysis machine (draw blood and put back into body) [15]
11. Measure CBP (cerebrovascular pressure reactivity) [16]
12. Helmet/headband that measures head circumference [17]
13. Immune response from swelling [18]
14. Caliper that correlates baby head to ICP/Poking baby heads (through baby hole) [19]
15. Measure energy of sound signal after passing the brain [20]
16. Resonant frequency (echolocation) [21]
17. Look at pupil of eye with camera or sensor [22]
18. Sensor that goes through eye to brain [23]
19. Transcranial Magnetic Stimulation [24]
20. Measure pressure by treating the neuron as a capacitor [25]
21. Ear pressure measurer that relates to ICP in the brain [26]
22. Blow your nose really loud (sinus pressure) and the pressure will relate to ICP [27]
23. Throat pressure gauge (through neck hole where brainstem goes) [28]

24. Predictive power of including several coefficients [29]

25. Relationship between ICP and ONSD [30]

To further evaluate the aforementioned ideas, each team member conducted a thorough literature search on the proposed solutions to obtain quantitative values with respect to the seven quantitative design specifications. If an idea was found to be unsafe or unfeasible, it was removed from further consideration. If two ideas were found to be highly similar, they were grouped into one general idea. At the conclusion of the literature search, nine feasible ideas remained.

Some of the techniques continuously display and update ICP information after a single setup procedure whereas other techniques are only able to read ICP at one time point. Due to this, we grouped the potential solutions into continuous measurement devices and single measurement devices as shown below. The names in parentheses indicate the terms with which the techniques will be referred to from here onwards.

Continuous Devices:

1. **Electrodes - Visual Evoked Potential Electroencephalography (EEG)**

   As shown in **Figure 3**, the patient wears electrodes on the back of their head and on their forehead (ground). The patient is then exposed to a visual stimulus (typically a checkered screen) which creates electrical activity in the brain called an evoked potential. Measuring this evoked potential reveals the time it takes for the visual stimulus to travel from the eye to the occipital cortex. The results are shown as a reading on an EEG and can be used to determine ICP [31].

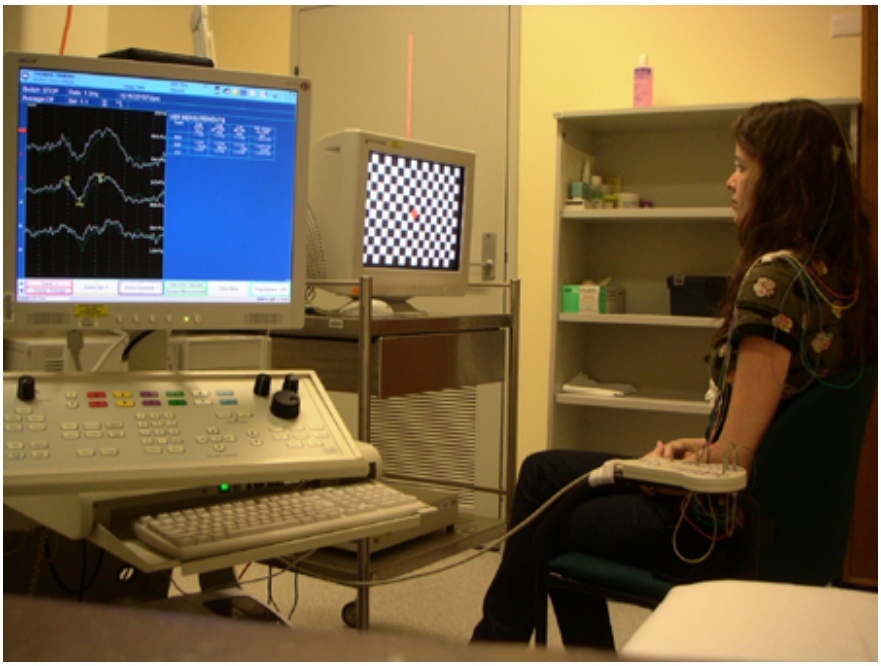

Figure 3: Visual Evoked Potential (VEP) Setup

2. **Electrodes - Ear/Auditory (Ear E)**

   The patient has a gold-coated electrode inserted into their ear canal and skin electrodes on their forehead (ground). The patient is then exposed to a sound stimulus of approximately 1000 Hz which induces current to flow through the transduction ion channels of the ears' auditory sensory cells. The phase changes of this electrical current, known as cochlear microphonics (CM), can be correlated with changes in ICP [11].

3. **Pressure from Vein/Artery (PVA)**

   The doctor makes a small incision in the wall of the cortical vein and inserts a fine polyethylene catheter for a distance of 1 - 2 cm into the vein to measure cortical vein pressure. This measurement can be correlated to ICP to obtain a pressure reading [12].

4. **Tympanic Membrane IR Sensor (TMIR)**

   Since the fluid-containing compartments in the inner ear and the cerebrospinal fluid space are connected, changes of ICP levels can lead to changes in the structure of the inner ear. Both tympanic membrane displacement and cochlear microphonic potential have been proven to share some correlation with ICP, which can lead to the development of an indirect, non-invasive method to monitor ICP [11].

5. **Resonant Frequency (Echo)**

   Previous research in Tissue Resonance Analysis has found that ICP changes can lead to variations in the pattern of mechanical vibrations in the body, especially the brain. Such changes in vibration pattern and resonance of brain tissue and fluid compartments can be detected via an ultrasound probe and then processed to output real-time ICP measurements [21].

6. **Sensor That Goes Through Eye to Brain (iSensor)**

   By making a small burr hole in the eye socket, it is possible to insert a small pressure sensor into the cranial space. Since the sensor will be in contact with CSF, it can directly measure ICP. The sensor can remain in the cranial space indefinitely and can transmit ICP readings via Bluetooth. This allows for ICP measurements with the accuracy of the standard ventriculostomy method, but with a less invasive procedure and the ability to monitor ICP for longer periods of time [32].

Single Use Devices:

7. **Relationship Between ICP and ONSD (ONSD)**

   Build-up of cerebrospinal fluid within the ventricle spaces is also associated with the dilation of optic nerve sheath diameter (ONSD), so analyzing optic nerve sheath of traumatic brain injury patient may also give information regarding ICP levels. This solution option involves utilizing ultrasound or other imaging methods and outputting a numerical value based on the correlation between ONSD and ICP [14].

8. **Immune Response through Enzyme-Linked ImmunoSorbent Assay (ELISA)**

Changes in ICP cause cells to release certain biomarkers, and the concentrations of these in patient blood can be correlated to ICP. Examples of proteins that have a correlation with high ICP include ICAM-1, interleukins, TNF, and TGF-β [18]. After taking a blood sample from the upper-arm veins, the concentration of the protein of interest can be quantified using an assay such as an enzyme-linked immunosorbent assay (ELISA), and this concentration can be used to estimate ICP using a linear regression [33].

9. **Fontanelle Palpitation (Fonta)**

   The fontanelles are areas in which an infant's skull has not fused, as shown in **Figure 4**. This means that the CSF is in direct contact with the fontanelle, so an increase in ICP will cause the CSF to exert more pressure on the fontanelle. Consequentially, the fontanelle will bulge outward. Measuring the degree of bulging of the fontanelle will provide a noninvasive method for quantifying ICP in infants.

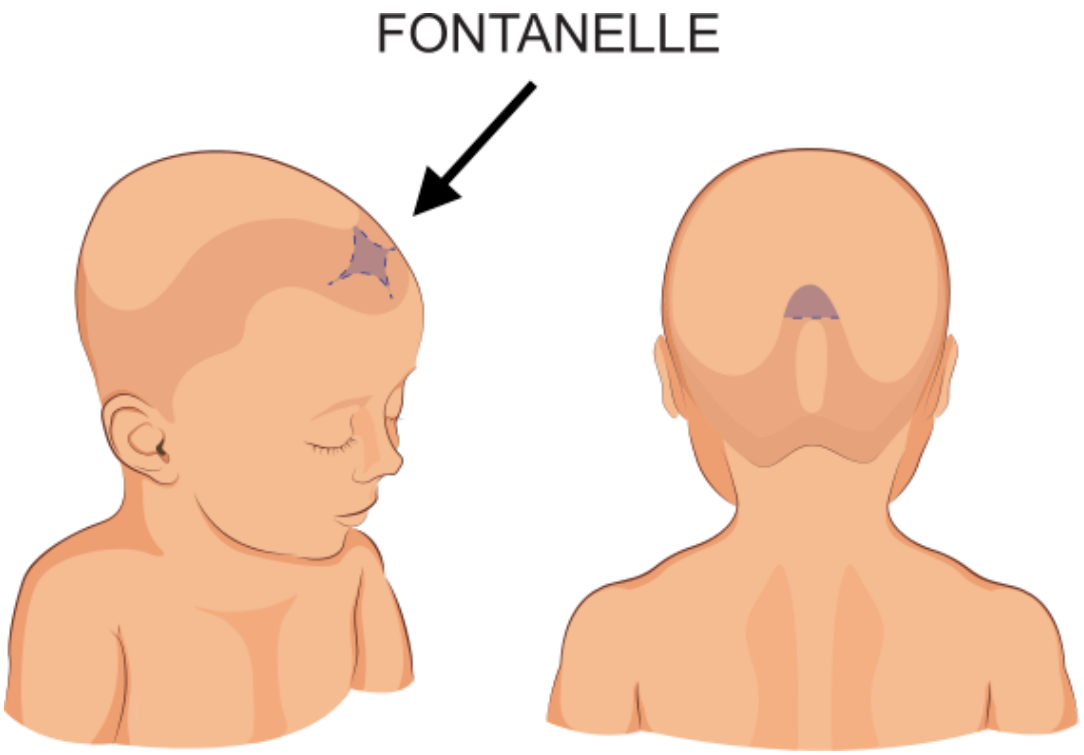

Figure 4: Fontanelle, the "Soft Spot" on the Head of Infants Below 18 Months Old

Next, we ranked the design specifications using a pairwise comparison chart to later screen the proposed solutions.

4.3.3 Determining Importance of Design Specifications

We utilized a pairwise comparison chart to determine the priority of each design specification (**Table 3**). This allowed us to more objectively determine the goals that our design solution should meet. The importance factor for each design specification is based on its percentage of total points, which is 18 points for single measurement devices and 21 points for continuous measurement devices.

Table 3: Pairwise Comparison Chart for Ranking Design Specifications

		Accuracy	Time delay	Time for operation	Total cost per use	Max Monitoring Time	Invasiveness	Maintenance Frequency
Accuracy			0	0	0	0	0	0
Time Delay		1		0	0	0	1	0
Time for operation		1	1		0	1	1	0
Total cost per use		1	1	1		1	1	0
Max Monitoring Time		1	1	0	0		1	0
Invasiveness		1	0	0	0	0		0
Maintenance Frequency		1	1	1	1	1	1	
Total		6	4	2	1	3	5	0
Importance Factor	Single Measurement	33.3%	22.2%	11.1%	5.6%		27.8%	0%
	Continuous Measurement	28.6%	19.0%	9.6%	4.7%	14.3%	23.8%	0%
Ranking		1	3	5	6	4	2	7

We determined that accuracy is the most important design specification because a device that produces a wildly inaccurate ICP measurement is not fit for clinical applications. With high accuracy, invasiveness is a critical parameter as our project motivation is to overcome the invasive nature of the currently used ventriculostomy technique. Time delay is the subsequent most important design specification, since the time difference between taking the measurement and obtaining a result would affect the doctor's ability to make quick interventions. Following this, maximum monitoring time is relevant as it dictates the duration of the ICP data acquisition period which influences the risk of developing complications in procedure. Time for procedure is also important because a device that can be set up quickly allows a doctor to more quickly collect data. Next, total cost per use is relevant as it can affect how many hospitals are able to implement our technology. Finally, frequency of maintenance dictates product upkeep which can affect total hospital costs through maintenance fees. However, we removed frequency of maintenance from further consideration because our pairwise comparison chart revealed that it was significantly less important than the rest of our design specifications. We then moved on to defining the scales of each design specification to later rank our design solutions using a Pugh Scoring Matrix.

4.3.4 Quantitative Five-Point Scales

Based on the research we did for the potentially feasible data acquisition methods, we created quantitative five-point scales for each design specification (**Table 4**). The value for each score was selected in a way so that the proposed solutions would cover at least four out of the five points for each design specification in the Pugh Scoring Matrix. The most optimal value for each design specification across all the solutions would earn a 5 and the least optimal would earn a 1. For example, the accuracy difference of our design solution with respect to ventriculostomy is desired to be as small as possible. A 5 was given to any solution with an accuracy difference of ± 1.4 cm H_2O, such as solution Fonta, and a 1 was given to any solution option with an accuracy difference of ± 13.6 cm H_2O, such as solution ELISA. In this way, we utilized the five-point scale of a Pugh Scoring Matrix to objectively quantify the performances of each solution. We developed separate time ranges for single measurement and continuous measurement devices with regards to time for operation, with a shorter range for single measurement devices as the procedure has to be repeated for each measurement, while continuous measurements only require setup once. In addition, single

measurement devices are not evaluated in the maximum monitoring time design specification as it not applicable.

Table 4: Five-Point Scale for Design Specification Metrics

Specifications		**Score**				
		1	**2**	**3**	**4**	**5**
Accuracy (cmH_2O)		>± 13.6	± 9.3- ± 13.6	± 5- ± 9.3	± 1.4- ± 5	< ± 1.4
Frequency of Measurement/ Time Delay (minutes)		>60	30-60	15-30	1-15	<1
Time for operation (minutes)	**Single Measurement**	>30	15-30	10-15	5-10	<5
	Continuous Measurements	>60	45-60	30-45	15-30	<15
Total cost per patient ($)		>2,500	1,500-2,500	500-1,500	100-500	<100
Max Monitoring Time (days)						
	Continuous Measurements	<1	1-6	6-14	14-30	>30
Invasiveness		Incision into the skull and brain	Catheterization	Drawing Blood	Contact with patient	Minimal contact with patient

4.3.5 Pugh Scoring Matrix

We used the finalized five points scales in conjunction with the pairwise comparison chart results to construct two different pugh scoring matrices for the single measurement devices and continuous measurement devices respectively. This allowed us to rank the proposed solutions based on overall quality as can be seen **Tables 5** and **Table 6** below.

Table 5: Pugh Scoring Matrix for Single Measurement Solutions

Specification	**Importance Factor**	**ONSD**	ELISA	**Fonta**
Accuracy	33.3%	4 (1.332)	1 (0.333)	5 (1.665)
Invasiveness	27.8%	4 (1.11)	3 (0.83)	4 (1.112)
Time Delay	22.2%	4 (0.888)	1 (0.222)	5 (1.11)
Time for Operation	11.1%	1 (0.111)	5 (0.555)	3 (0.333)
Cost per Use	5.6%	3 (0.168)	4 (0.224)	2 (0.112)
Total	100%	3.609	2.164	4.332
Ranking		2	3	1

Table 6: Pugh Scoring Matrix for Continuous Measurement Solutions

Specifications	**Importance Factor**	EEG (VEP)	Ear E	Pva	**Echo**	TMIR	iSensor
Accuracy	28.6%	4 (1.144)	2 (0.572)	3 (0.858)	5 (1.43)	2 (0.572)	4 (1.144)
Invasiveness	23.8%	4 (0.952)	4 (0.952)	2 (0.476)	4 (0.952)	4 (0.952)	1 (238)
Time Delay	19.0%	3 (0.57)	4 (0.76)	5 (0.95)	5 (0.95)	4 (0.76)	5 (0.95)
Time for Operation	9.6%	2 (0.192)	2 (0.192)	1 (0.096)	3 (0.288)	4 (0.384)	1 (0.096)
Max Monitoring Time	14.3%	1 (0.143)	1 (0.143)	2 (0.286)	1 (0.143)	3 (0.429)	5 (0.715)
Total Cost per Use	4.7%	3 (0.141)	3 (0.141)	4 (0.188)	3 (0.141)	3 (0.141)	1 (0.047)
Total	100%	3.142	2.76	2.854	3.904	2.238	3.19
Ranking		4	6	5	1	2	3

Finally, we pooled the results from the Pugh Scoring Matrices into a final table that illustrates the overall performance of each technique. This can be seen in **Table 7**. The three most promising technologies, in order of increasing quality, are ONSD quantification, Echo Ultrasound, and Fontanelle.

Table 7: Final Rankings for Potential Data Acquisition Solutions

	EEG (VEP)	Ear E	Pva	**Echo**	TMIR	iSensor	**ONSD**	ELISA	**Fonta**
Score	3.142	2.76	2.854	**3.904**	3.238	3.19	**3.609**	2.164	**4.332**
Rank	6	8	7	**2**	4	5	**3**	9	**1**

4.3.6 Decision on the Patient Group

Our team visited the neonatal intensive care unit at Texas Children's Hospital to obtain more understanding on the design challenge. Under the guidance of our clients, we observed and performed the fontanelle palpation method on several babies. This method consists of estimating ICP based on feeling the "bulginess" of the fontanelle. This visit made us realize that the only currently available methods to estimate ICP ae either qualitative or highly invasive. Furthermore, to our knowledge, there are currently no methods in development to noninvasively obtain a quantitative measurement of ICP in patients younger than 18 months old. Therefore, we decided to focus on this patient group.

4.3.7 Focusing on the Fontanelle

After deciding the patient group, we evaluated the three options based on research available, reliability, and feasibility. Despite the accessibility of the fontanelle, we learned that previous research placed less focus on utilizing non-invasive sensors to measure ICP through the fontanelle [34]. For our second best choice, there is little available information on utilizing the resonant frequency of body tissue to predict ICP [21], and the exact mechanism behind the observations seem beyond the scope of this problem. ONSD, while being the most widely practiced technique among the three solution options, is both highly inter-patient dependent and inter-observer dependent [4], limiting its accuracy when establishing the quantitative relationship with ICP levels. Considering that our target users will be infants younger than 18 months old with skulls not entirely fused yet, we decided to focus on Fonta. We then conducted further research and brainstorming to generate potential solutions using the fontanelle. We grouped our ideas into two categories: 1) attachment methods (**Figure 5**, **Figure 6** and **Figure 7**) and 2) measurement methods (**Figure 8**, **Figure 9** and **Figure 10**), as included in **Section 10 Appendix**. Below examples of some of the brainstormed ideas.

Examples of Attachment Method:

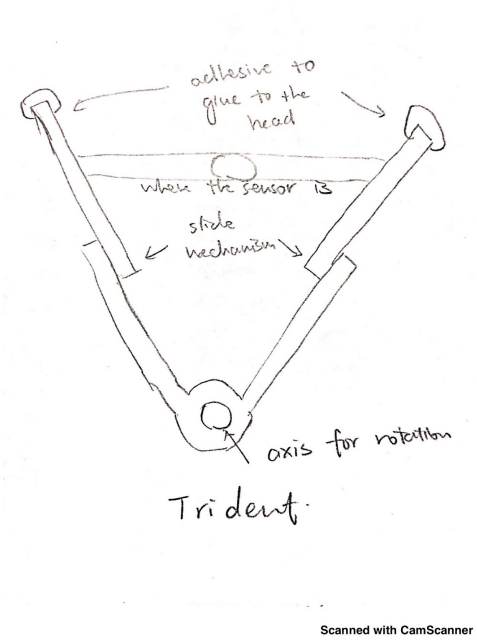

Figure 5: Trident. The three fixation points (2 at the end of the arms and 1 at the axis of rotation) ensures the proper attachment and the sliding and rotation of arms allow for placement of the sensor to be right above the fontanelle.

Figure 6: SurePulse Heart Rate Monitoring Cap. A novel product in the market for measuring the heart rate from babies [35].

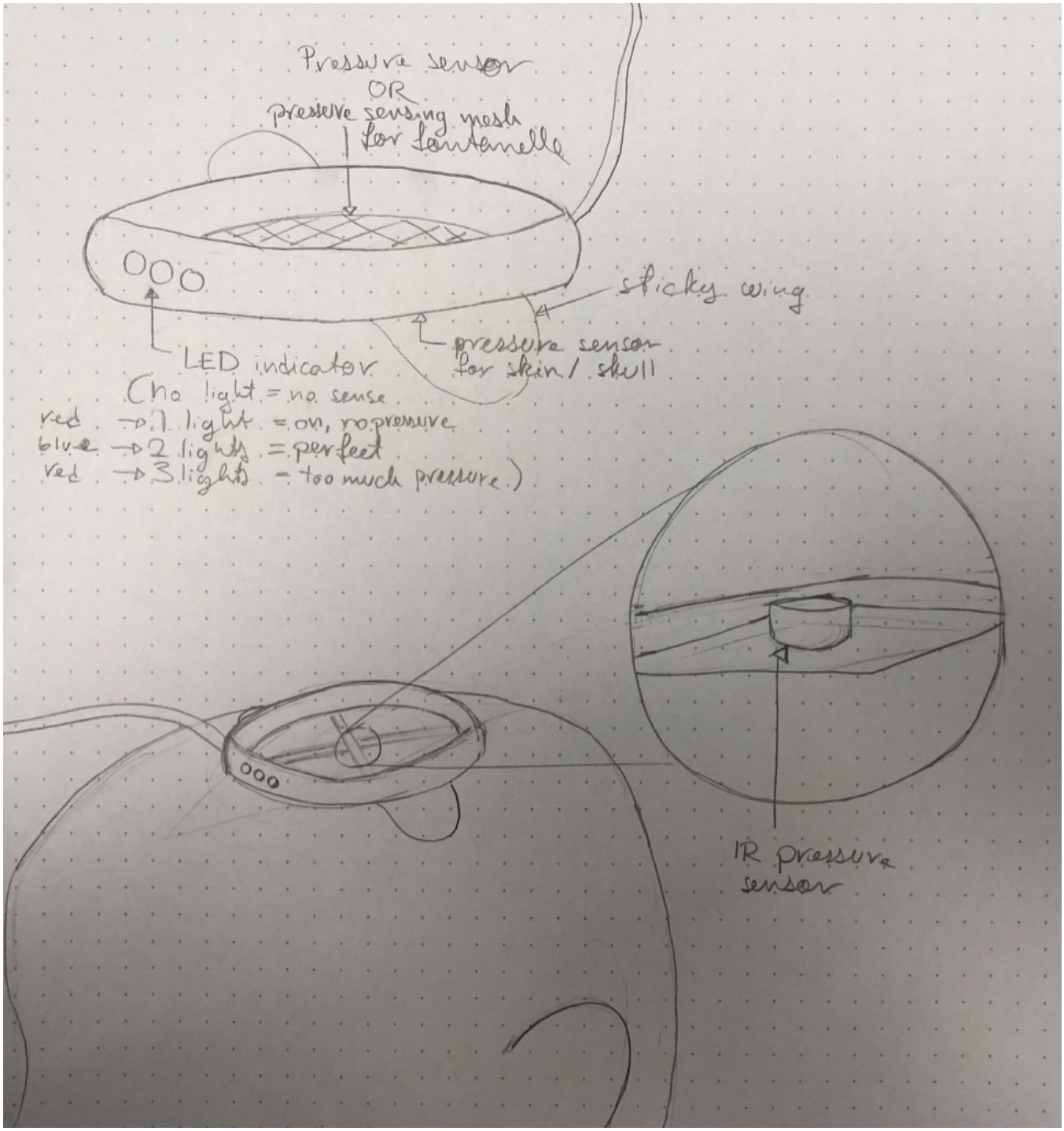

Figure 7: LED Casing. This casing contains three LEDs that will light up to indicate if the sensor is properly placed.

Examples of Measurement Method:

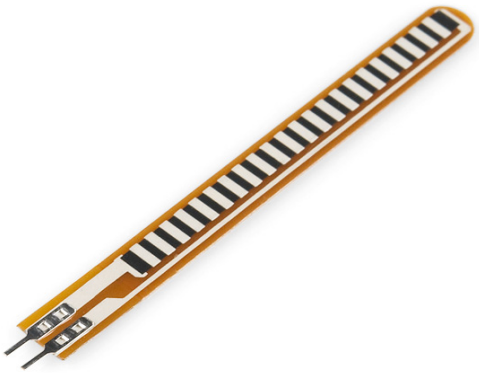

Figure 8: Flex Sensor. A sensor which varies its resistance level based on the bending angle.

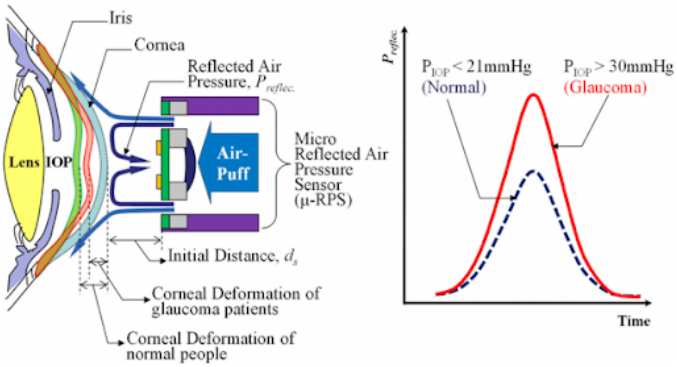

Figure 9: Air Puff Tonometer [36]. A method to measure eye pressure based on the flow of air bounced back from the cornea.

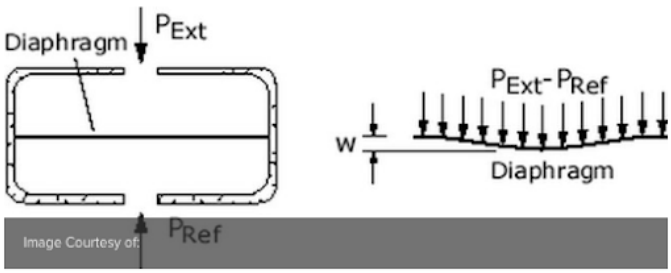

Figure 10: Left: Diaphragm Pressure Gauge. Right: The diaphragm deflects to indicate variances in pressure with respect to the pressure of a known liquid. [37]

After the discussion, we did an anonymous vote for the attachment and measurement solution through giving each option a rating between 1 and 3, with 1 being the least feasible and 3 being the most feasible option. Based on the results, we decided that we would focus on a combination for Trident and LED Casing for the attachment method and Flex Sensor for a measurement method for the first round of prototyping.

4.4 From Conceptual Design to Prototyping

Adopting the Engineering Design Process, our team was able to brainstorm 79 potential data acquisition methods, thoroughly examine them through extensive literature review and found 9 technologies that were feasible for production falling into both categories of single measurement devices and continuous measurement devices. The top three potential solutions were Echo, ONSD, and Fonta. After conducting extensive research and consulting our clients, we moved forward with measuring ICP through the fontanelle for patients below 18 months old with the hope of bringing tangible benefits to this underserved population. A proof of concept prototype was first generated in medium fidelity, which we used as the basis to improve on.

4.4.1 Medium Fidelity Prototyping

By end of the fall semester (December 2018), we produced our first functional prototype as shown in **Figure 11**, which consists of three components: the attachment method, the hardware and the coding.

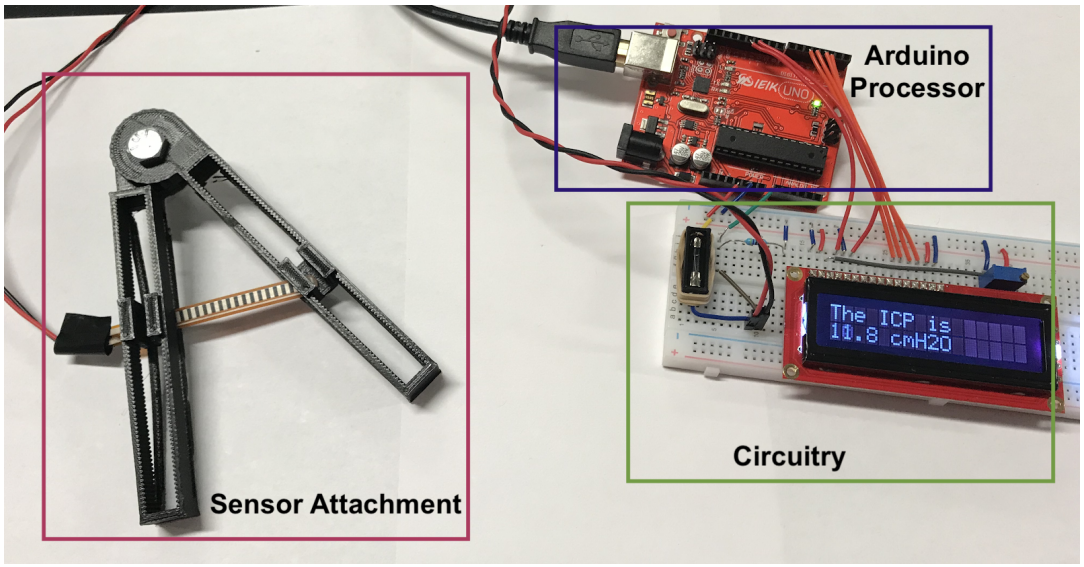

Figure 11: First Functional Prototype

This prototype utilizes the “Trident” attachment method, which is composed of two “arms” that will align with the sides where the unfused skull and skin are in contact. The arms can rotate around with respect to the central fixed axle and two clips within the arms house the flex sensor, together giving the structural stability when attaching the sensor onto patient’s head. However, feedback from our mentors and clients indicated that this attachment method may be far too stiff and would not be able to adhere to the curvature of infant head. The attachment was further optimized based on these suggestions in next stage of prototyping.

We used an Arduino UNO board to process the written code, which contains a mathematical model built from ICP values and bending angles of the fontanelle from previous research, described in detail in **Section 4.2.1**. To reduce the chance of electrical shock, a fuse was included in the circuitry. The reading is then displayed on the LCD screen.

Although only a proof of concept, this prototype was able to demonstrate the feasibility of using flex sensor to gauge ICP, with measuring fontanelle flexion being the intermediate step. Preliminary testing also showed promising results, of accuracy level within ± 10 cm H_20 for ICP levels between 0 and 15 cm H_20 and ± 5 cm H_20 for ICP levels between 15 and 60 cm H_20. However, we noticed that switching to a different flex sensor would lead to extremely low or high ICP values. Since the output ICP value is linearly read off from the resistance value of the flex sensor, we suspected that each flex sensor may have slightly different range of working resistance values and this could also lead to the insensitiveness we observed in the accuracy testing. Therefore, a way to calibrate for this variation is in need.

4.4.2 Optimization and Added Features

Attachment:

To ensure the smooth attachment of our device, we constructed two possible solutions: one utilizing the wound dressing DuoDERM, shown in **Figure 12** and the other utilizing straps and velcro, shown in **Figure 13**. Both attachment methods allowed for more secure adherence of the sensor to the infant's head. However, since the strap method only relies on the tightness of fabric to hold down the sensor, we were worried that the location of the sensor would not always remain directly on top of the fontanelle due to movement. This, in turn, would lead to inaccuracies in measurements. Additionally, the processes of manufacturing the straps and securing the straps are both more complicated and time-consuming. Therefore, we decided to move forward with the DuoDERM wound dressing attachment method, following the recommendation by our clients.

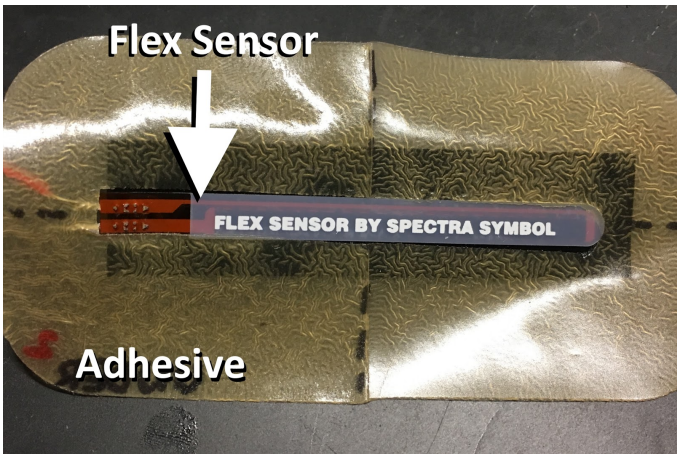

Figure 12: Attachment Method 1 - Using Wound Dressing to Adhere to Skin Near the Fontanelle

Figure 13: Attachment Method 2 - Using Straps to Secure Under the Chin and Around the Head

Calibration for Sensor Manufacturing Error:

To account for the differences in working range of resistance values of individual flex sensor, we implemented a calibration mechanism that helps to build the basic linear relationship between resistance values and ICP levels. This mechanism utilizes the "calibration blocks" of pre-determined bending angles shown in **Figure 14**, where the user would put the sensor on top and press a button to inform the code to take note of the respective resistance reading. However, repeated functionality testing showed that these blocks, with a thickness of less than 0.3 inch, generated great difficulty in trying to achieve the correct placement of the sensor while pressing the button. As shown in **Figure 15**, calibration blocks with larger surface area were designed to reduce the struggle and ensure the establishment of an accurate relationship between sensor resistance and ICP values.

Improvements mentioned here are the essential changes occurred during the prototyping stage. However, we have also included other features to enhance our prototype both in accuracy and ease-of-use in the following prototyping process. These features include a calibration mechanism to account for the head curvature which also contributes to the bending angle measured by the sensor, an alert system that shines red light and alarms a buzzer when ICP reaches dangerous levels and a data storage module for easier access and sharing of the measured ICP values. These are described in detail in **Section 4.2.4**.

Figure 14: Initial Design of Calibration Blocks

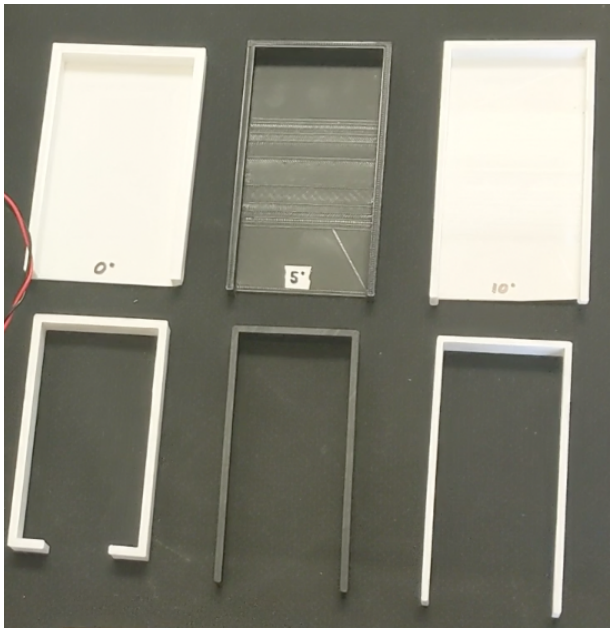

Figure 15: Iterated Design of Calibration Blocks

Upon optimizing the attachment method, correcting for manufacturing error of the flex sensor, accounting for the curvature of the head and adding user-friendly features, we arrived at our final design solution.

5 Final Design

5.1 Device Description

Our final design, as shown in **Figure 16**, consists of two major components. The first component, the DuoDERM wound dressing, houses a flex sensor and allows for the attachment onto patient's head. A plastic box is used to hold the other component, the electronics, which are composed of a printed circuit board for the circuitry and an Arduino Uno microcontroller. In the following sections, we will walk through both the software and the hardware of our design and how to assemble parts of the device.

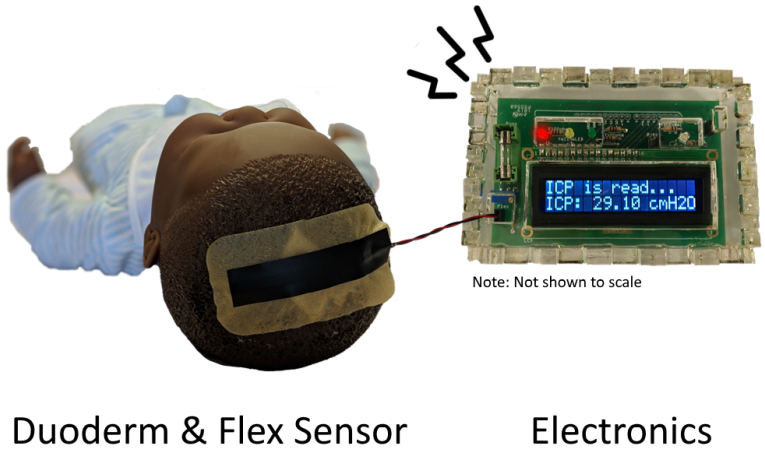

Figure 16: Picture of Final Prototype

5.2 Software

The software for this device contains four main components: 1) signal processing, 2) calibration, 3) the alert system, and 4) data storage. The following sections describes each of these components.

5.2.1 Signal Processing

The main function of this component is to correlate ICP values with the displacement angle of the fontanelle. Through such relationship, the device is able to produce accurate readings of ICP once detecting changes of flexion of the fontanelle after placed on top of the patient's head. The device achieves this goal using a mathematical relationship established based on data obtained from Bunegin *et al* (**Figures 17** and **Figure 18**) [34]. Bunegin *et al.* measured the vertical displacement of a three-cm long fontanelle from 0 to 40 mmHg ICP values; the device, in turn, utilizes a third order polynomial fit that describes the relationship between the deflection angle of the fontanelle (the angle between displaced fontanelle and baseline of two fontanelle/bone margins) extrapolated from the displacement readings and the ICP values. With an R^2 value of 0.97, this model demonstrates a strong correlation between the two variables and serves as the basis of our software.

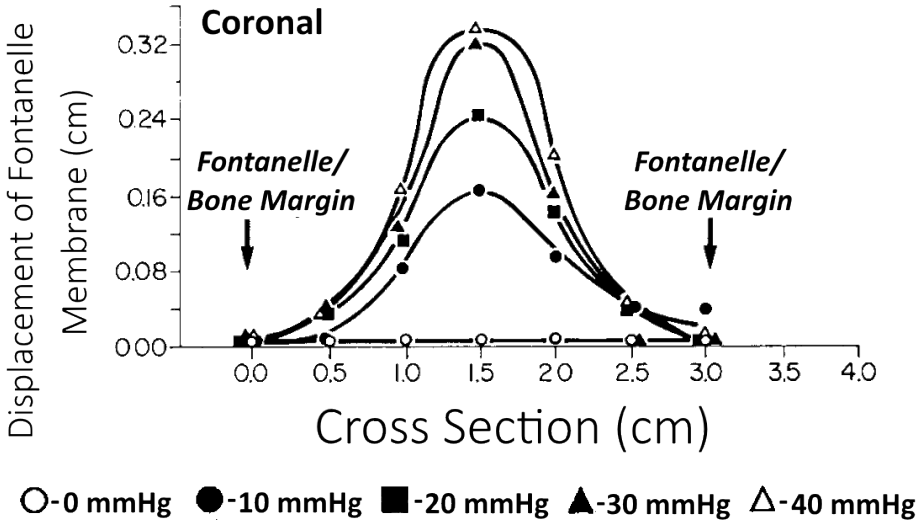

Figure 17: Vertical Displacement of Fontanelle Membrane at ICP ranging from 0 to 40 mmHg. Adopted from Bunegin *et al.*[34]

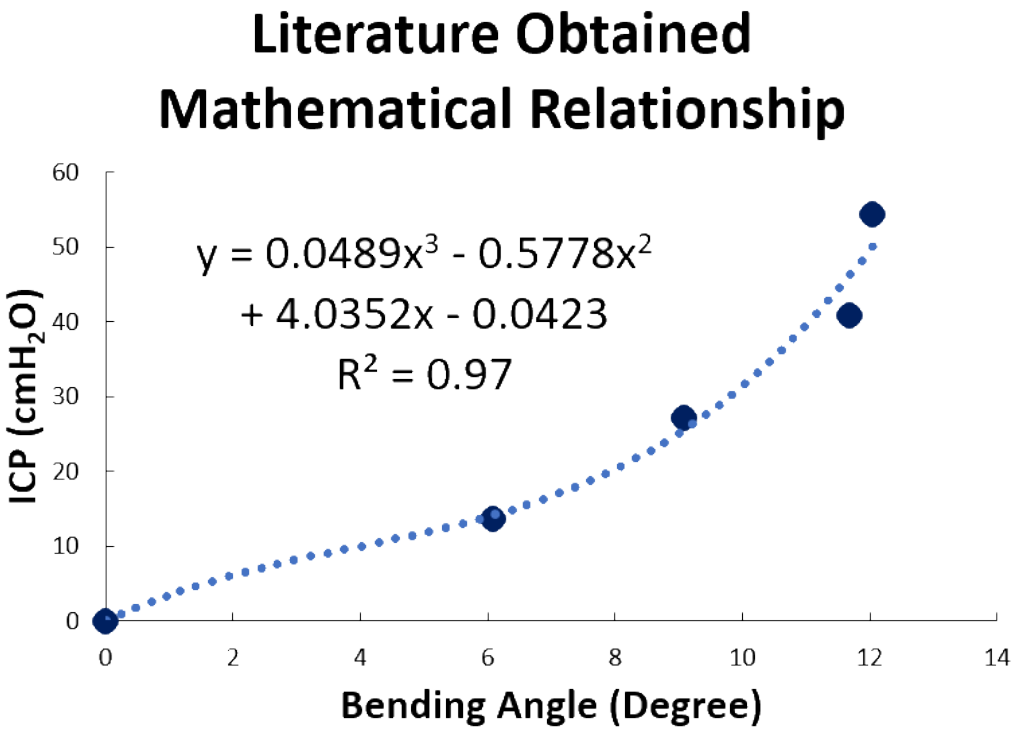

Figure 18: Third Order Polynomial Fit for ICP Values and Bending Angle of the Fontanelle Calculated from Work of Bunegin *et al.*[34]

5.2.2 Calibration

For Manufacturing Error:

Our device measures deflection of the anterior fontanelle using a Flex Sensor, which has resistance that varies linearly with bending angle. Our device measures the resistance of the Flex Sensor and then uses this linear relationship to estimate the bending angle of the fontanelle, which can then be correlated to ICP as described previously.

Because there is some variance in the resistance of different Flex Sensors when bent at a given angle, each sensor will have a different equation describing the relationship between resistance and bending angle. To account for this, our device can be calibrated to create this linear equation upon startup.

Calibrating the device involves measuring the resistance of the Flex Sensor at three set bending angles: 0°, 7°, and 12°. These values are selected based on the physiological relevance to the commonly observed ICP levels in infants. In order to accurately and consistently bend the Flex Sensor at these angles, we have designed and 3D-printed the calibration blocks shown in **Figure 19**. Placing the DuoDERM with flex sensor attached in the middle on these blocks and pressing down on the DuoDERM using the pressing tool will bend the flex sensor at the specified angles. The resistance values are then recorded every time the button is pressed for establishing the linear relationship between ICP values and resistance of the flex sensor.

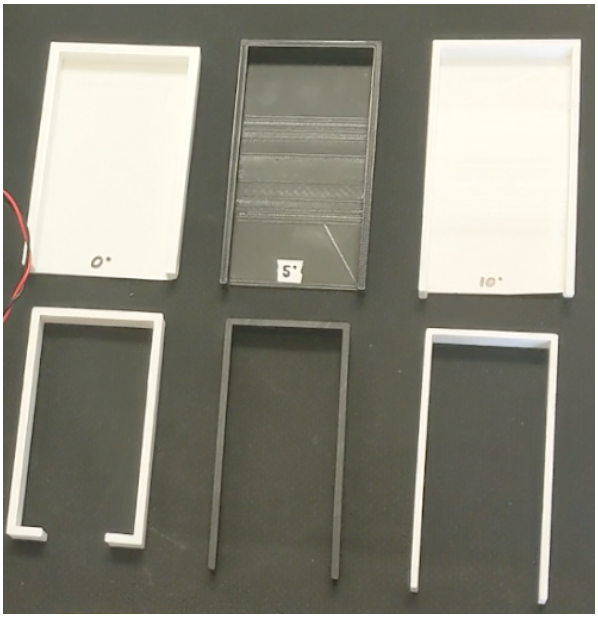

Figure 19: Final Design of Calibration Blocks

After measuring the resistance for all three angles, the device will generate a least squares regression line for correlating the resistance of the Flex Sensor to bending angle.

For Head Curvature:

Because the area of the head surrounding the fontanelle almost always has some curvature, the resistance of the flex sensor when placed on a patient will vary due to both the deflection of the fontanelle and the curvature of the patient's head. Because this additional resistance will introduce error into the ICP calculation, we added two additional calibration steps to measure and subtract out the added resistance due to head curvature.

Calibration for head curvature occurs after calibration for manufacturing error. The user first places the DuoDERM with attached flex sensor on the patient's head such that the flex sensor is on the anterior end of the anterior fontanelle and in a left-right orientation. The user then presses on the DuoDERM to bend the flex sensor until it follows the curvature of the head and presses the button on the device. This process is then repeated for the posterior end of the anterior fontanelle. Because both locations lie outside of the anterior fontanelle, the patient's ICP will not affect how the flex sensor bends.

In order to reduce the error due to head curvature, we first take the average of the resistance values at the two parts of the head. The two values were averaged because we assumed that the curvature of the head at the center of the anterior fontanelle would have characteristics of the curvatures at both ends of the fontanelle. We then subtract the resistance of the flex sensor when placed on the 0° block. This value approximates the additional resistance of the flex sensor when placed on the center of the fontanelle, and when calculating the bending angle of from the resistance of the flex sensor, the value for resistance used in the linear regression equation is the flex sensor resistance minus the head curvature resistance value.

5.2.3 Alert System

The device features an alert system that will have three colored indicators for: 1) normal ICP (when ICP is less than 15 cmH_2O), 2) medium ICP (when ICP is between 15 and 20 cmH_2O), and 3) high ICP (when ICP is more than 20 cmH_2O). As shown in **Figures 20**, a green LED will light up when the device measures an ICP <15 cmH_2O and a yellow LED will light up when the device measures an ICP between 15 and 20 cmH_2O. If the ICP is <20 cmH_2O, the red LED will light up, and the buzzer alarm will sound in order to alert the operator.

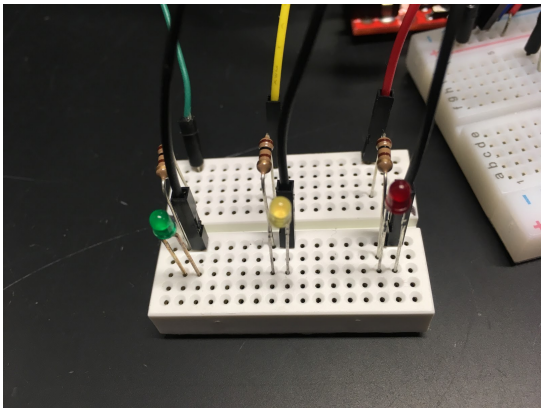

Figure 20: Proof of Concept Prototype of Alert System LEDs

5.2.4 Data Storage

The device also contains a component for storing the ICP values captured over time. Currently, the program records ICP values every 5 minutes into a .txt file in the external secure digital (SD) card (**Figure 21**) for easier transferring to Excel or other software for analysis. This time interval is selected based on the fact that measuring ICP changes over prolonged periods has higher physiological relevance than noting all the spikes and troughs of ICP. This way, ICP measurements can be recorded over days and shared across medical professionals.

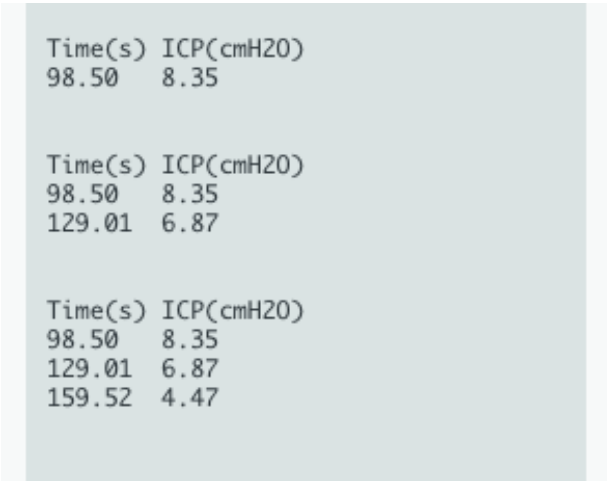

Figure 21: Display of Stored ICP Values Measured Every Half Minute

5.3 Hardware

The hardware for this device contains an Arduino Uno microcontroller and six main functional components: 1) the safety fuse, 2) the Flex Sensor, 3) the LCD screen, 4) the calibration button, 5) the calibration LED, 6) the alert system LEDs, and 7) the piezo buzzer. The Fritzing circuit diagram for the hardware is shown in **Figure 22**, and a parts list for all the components listed is included in the next section. The printed circuit board (PCB) where the circuit components of our device are housed and the Flex Sensor which is the core of our device are described in more detail in further sections.

The circuit in **Figure 22** shown above is what we are currently using for our PCB. However, we also have a prototype that utilizes an Arduino Mega microcontroller to allow more pin space. This allows us to include data storage and a RGB alert LED in place of the three alert LEDs. The Arduino Mega prototype (as shown in **Figure 23**) has seven main components: 1) the safety fuse, 2) the Flex Sensor, 3) the calibration button, 4) the calibration LED, 5) the RGB alert LED, 6) the SD card reader, and 7) the LCD screen.

5.3.1 Parts List

The components needed to create this device are listed in **Table 8**. The total component cost of the device is $108.42 per device. Of these components, only the Flex Sensor and the DuoDERM adhesive need to be disposed of for each use of the device, meaning the reusable device core would

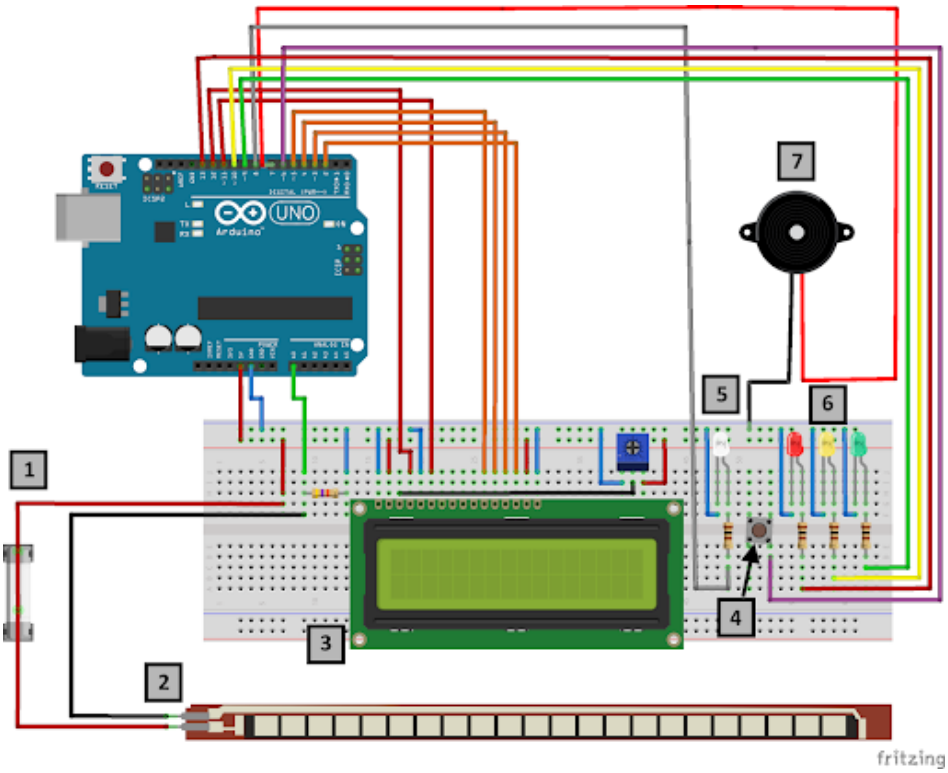

Figure 22: Fritzing Circuit Diagram for the Device

account for $98.07 of the total component cost and each disposable adhesive and Flex Sensor bundle would account for $10.35 of the total component cost.

5.3.2 Printed Circuit Board (PCB)

When manufactured for clinical use, this device will be composed of a printed circuit board (PCB) with the necessary components soldered on. A diagram of the device's current PCB prototype is shown in **Figure 24**. This PCB board prototype demonstrates how portable and compact the device will be as shown in **Figure 25**. The attachment port allows for the flex sensor to by plugged in and out so that the portion of the device that interfaces with the patient can be replaced while the main device is reusable. The device also has a safety fuse which protects the patient and the operator from any potential electrical shocks. A new PCB will be designed for the current device's design in the future.

5.3.3 Flex Sensor

Our device employs a strain gauge sensor, the Spectra Symbol Linear Flex Sensor 2.2", whose resistance changes based on device flexion. The Flex Sensor is the core of our device and is used to measure the fontanelle angle of flexion on the patient's head using these changes in resistance. As the sensor bends from 0° to 180° its resistance increases from 25 kΩ to 125 kΩ with a tolerance of ± 30%. It has an active length of 2.2" and a total length of 2.9", and is 0.25" wide and 0.017" thick. We selected this flex sensor so that the fontanelle of an average infant can be fully covered, which is 0.826" in length. The Flex Sensor is usable at a temperature range from -35 °C to +80 °C making it safe to use in hospitals kept around room temperature.

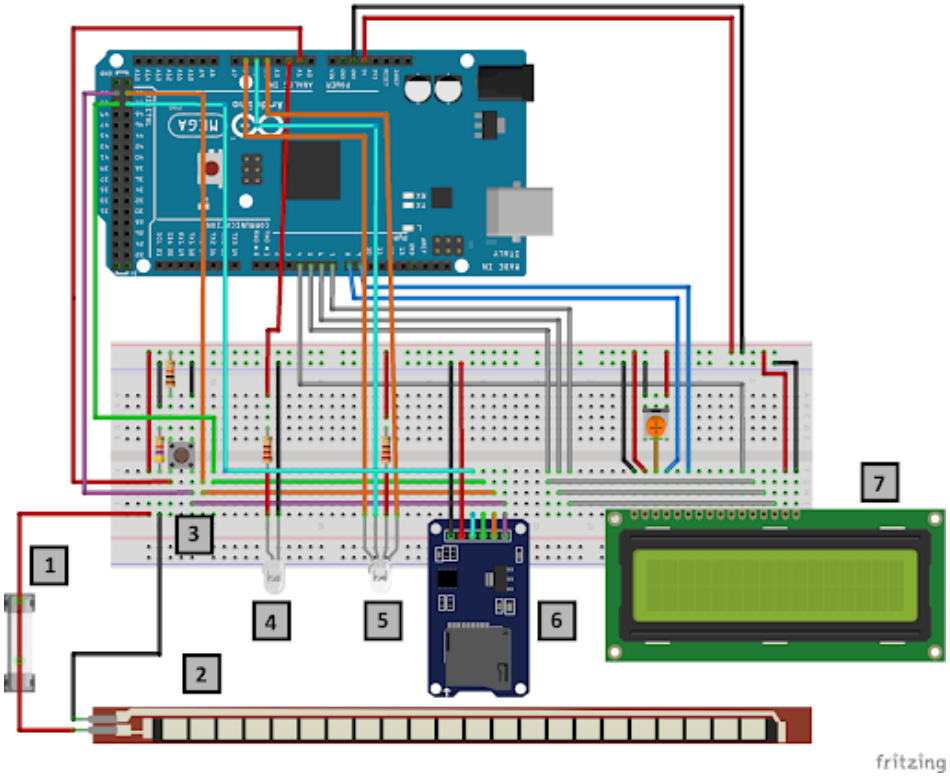

Figure 23: Fritzing Circuit Diagram for the Arduino Mega Prototype

Table 8: Manufacturing and Component Costs of Device. Disposable components are written in *italics*.

	Component Name	**Part Number**	**Price ($)**
Circuitry	Sparkfun Arduino Redboard	DEV-13975	19.95
	Printed Circuit Board	N/A	47.64
	Spectra Symbol 2.2" Flex Sensor	*SEN-10264*	*8.95*
	LCD Screen	B071Y6JX3H	6.20
	10 kΩ Potentiometer	COM-09806	0.20
	Fuse	T2AL250V	1.40
	Resistors and Wires	N/A	1.00
	Red LED	N/A	0.10
	Yellow LED	N/A	0.10
	Green LED	N/A	0.10
	White LED	N/A	0.10
	Buzzer	ZW0124	7.89
	Button	N/A	0.50
Casing	DuoDERM Extrathin Wound Dressing	*SKU-187900*	*1.40*
	0.25" Thick Acrylic	N/A	12.89
Total			108.42

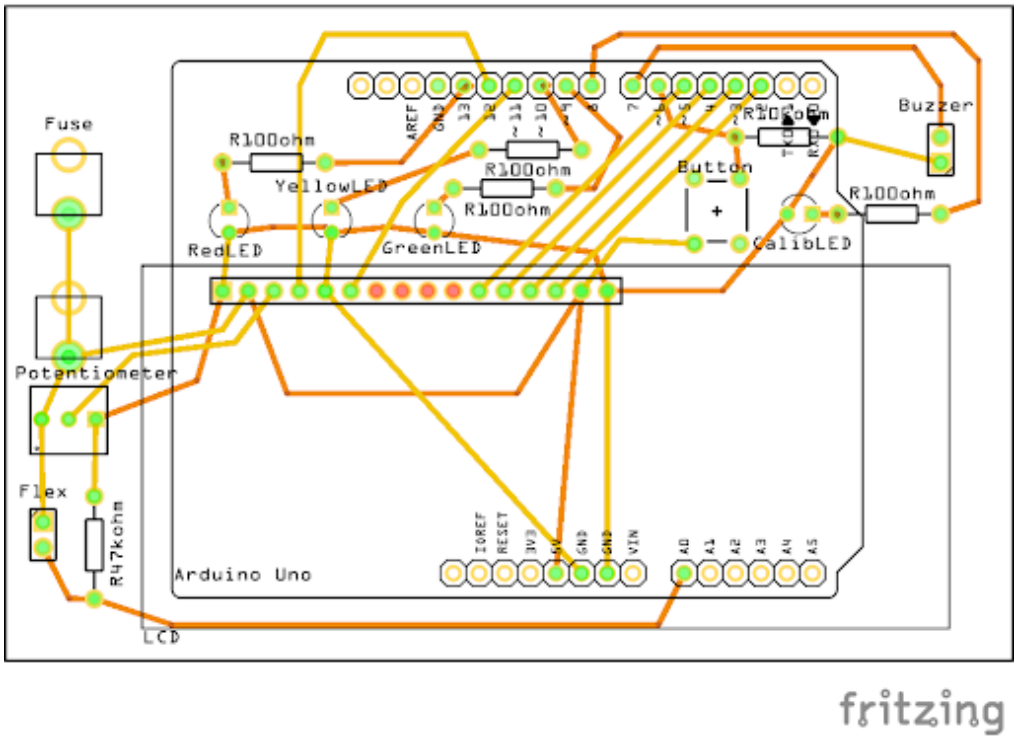

Figure 24: Fritzing Printed Circuit Board Diagram for the Previous Device Prototype

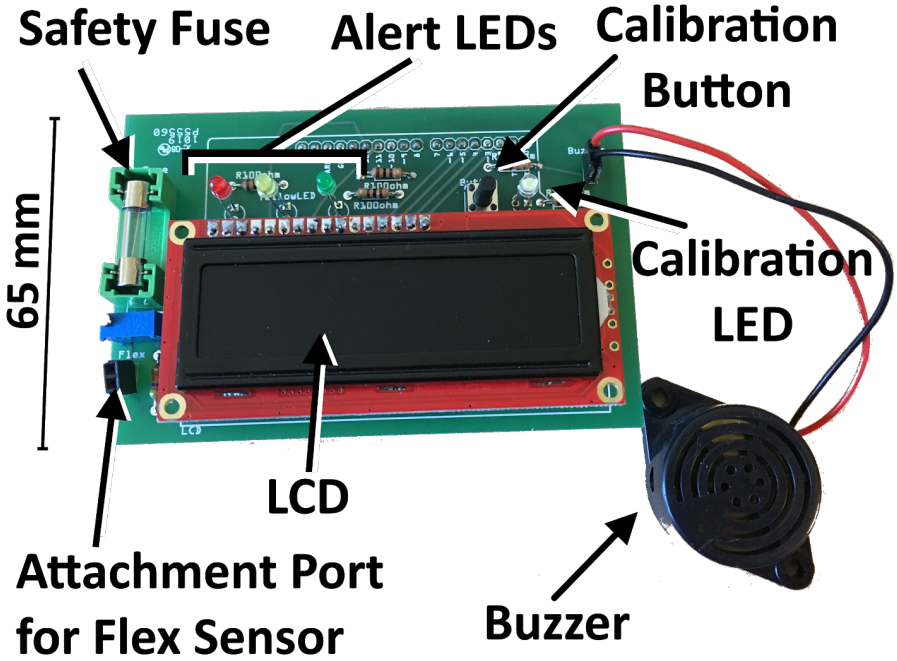

Figure 25: Functional PCB Board and Components Connected to the Arduino Microcontroller

5.3.4 Adhesive Attachment Method

The Flex Sensor is kept in place on top of the patient's head through a flexible adhesive casing. Our prototype employs a polyurethane DuoDERM Extra Thin CGF Dressing which is currently in

use in the Texas Children's Hospital Neonatal Intensive Care Unit. The adhesive is 0.023" thick, and provides a sterile, biocompatible barrier between the electrical components of the Flex Sensor and the patient's head. The adhesive is waterproof and easily removed, but allows for long-term (>7 days) adhesion of the device on the patient's head.

The Flex Sensor is attached on top of the adhesive as shown in **Figure 26** and wired to the rest of our device. A cross pattern is drawn on top of the flex sensor to show proper placement of the DuoDERM on the patient's head as the cross should align with the center of the fontanelle.

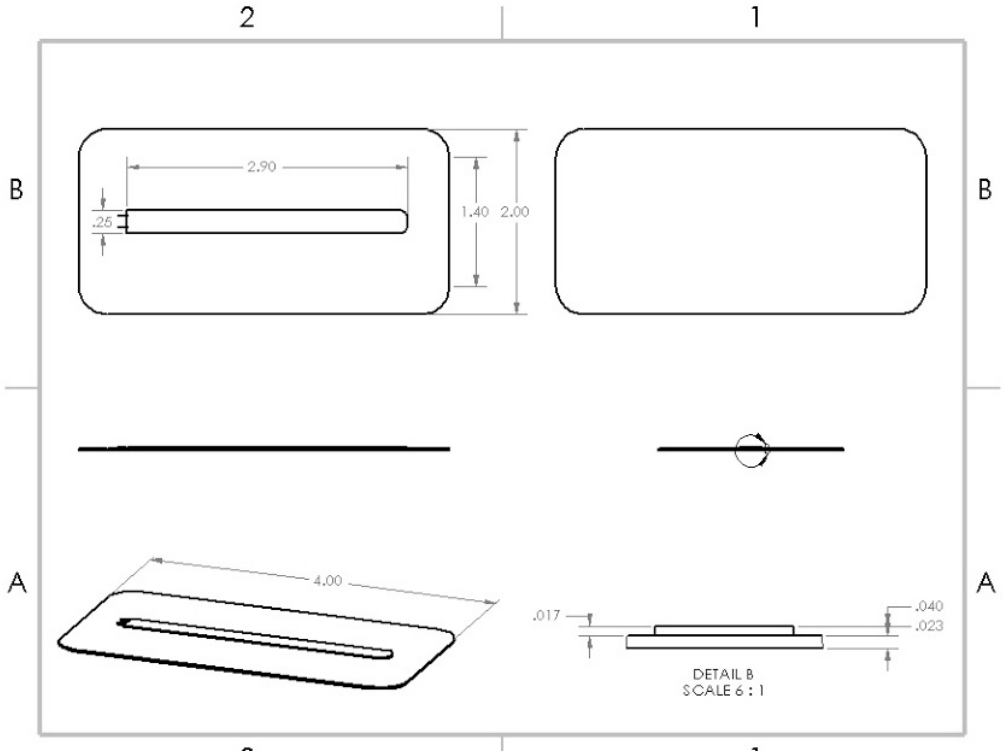

Figure 26: Engineering drawings of adhesive attachment method for our device fitted with the flex sensor. All measurements are in inches.

5.4 Assembly Instructions and Labor Burden and Materials

5.4.1 Assembly Instructions

1. Solder a male:male connector to each solder tab of a flex sensor. The edge of the flex sensor with the solder tabs is the left edge of the flex sensor; the opposite edge is the right edge, and so on.

2. Remove a DuoDERM Extrathin Wound Dressing from packaging

3. Orienting both the adhesive and flex sensor lengthwise, place the flex sensor on the top of the adhesive. Make sure that the entire sensor lies on the DuoDERM.

4. The left edge of the flex sensor should be 0.55" from the edge of the DuoDERM and the bottom edge of the flex sensor should be 1.875" from the bottom edge of the DuoDERM.

5. Use a piece of electrical tape to secure the entire flex sensor, minus the soldered wires, to the DuoDERM.

6. Follow the Fritzing diagram below to solder the red LED, yellow LED, green LED, white LED, button, 10 kΩ poteniometer, buzzer, 4 100 Ω resistors, and fuse to the printed circuit board. **Do not** solder the flex sensor to the printed circuit board.

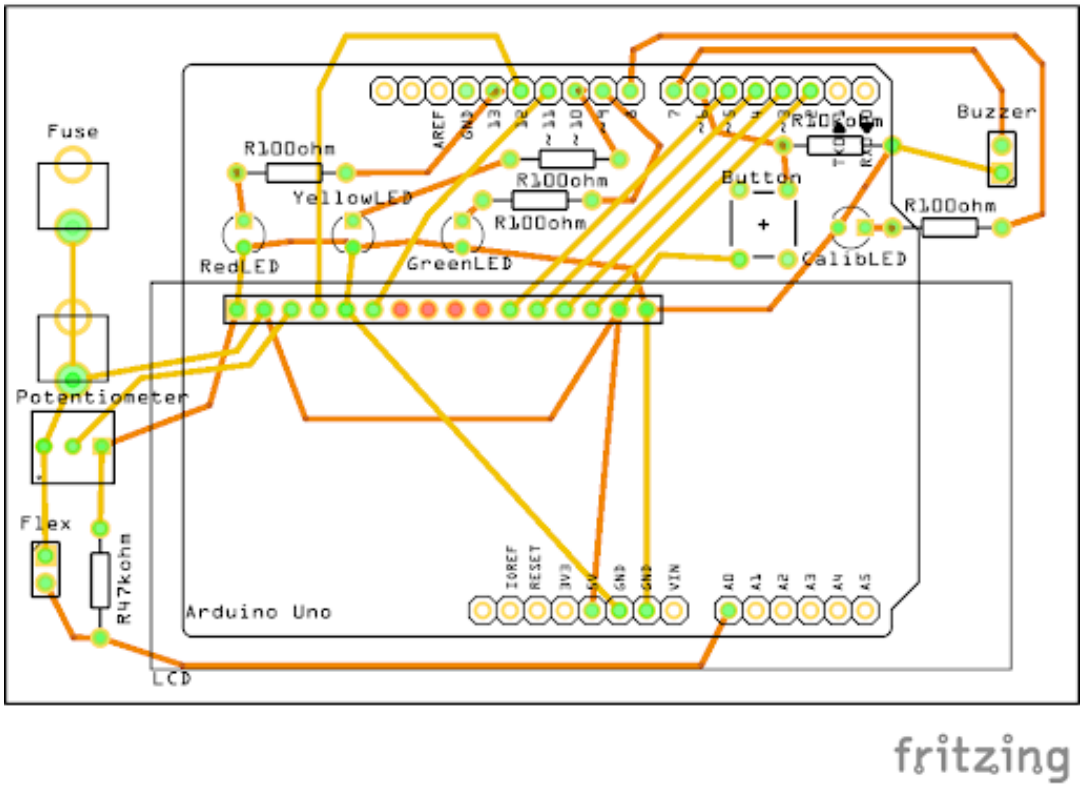

Figure 27: Fritzing diagram for the printed circuit board.

7. Connect the LCD screen to the 16 pins in the middle of the printed circuit board.

8. Connect the printed circuit board to the Sparkfun Arduino Redboard by connecting the pins at the top and bottom of the printed circuit board to their corresponding pins on the Arduino board. Note that all 18 pins on the top and all 14 pins at the bottom of the board must connect to the Arduino board.

9. Use a 3D printer to print the 0°, 7°, and 12°calibration blocks. Recommended to use 15% infill percentage, a 0.3 mm layer height, and print using poly(lactic acid) (PLA)

10. Use the soldered wires to connect the flex sensor to the connection port on the bottom left of the printed circuit board.

11. Power the Arduino board by plugging in the included USB adapter to the port on the bottom left of the Arduino board.

5.4.2 Low Scale Production

Assume a $40.00 per hour labor cost for all calculations.

Task	Materials Required (cost)	Total Material Cost ($)	Labor Cost ($)	Total Cost ($)
Solder Flex Sensor Wires	Flexs sensor (8.95), solder (negligable), wires (negligable)	8.95	4	14.95
Construct PCB	Manufactured PCB (47.64), 4 LEDs (0.40), 1k potentiometer (0.95), LCD (5.99), button (0.50), fuse holder (0.78), 1N4001 diode (0.15), 0.15 µF capacitor (0.25), buzzer (7.89)	63.65	40	103.65
Add Flexsensor to Adhesive	soldered flex sensor (0.00), duoderm extrathin wound dressing (1.40), electrical tape (negligable)	1.4	4	5.40
Manufacture Calibration Blocks	Cost to run 3D printer (10.24)	10.24	4	14.24
Manufacture Microcontroller Casing	Acrylic (12.89)	12.89	40	52.89
Total Cost				**191.13**

5.4.3 Medium Scale Production

Task	Materials Required (cost)	Total Material Cost ($)	Labor Cost ($)	Total Cost ($)
Solder Flex Sensor Wires	Flexs sensor (6.00), cost to run reflow oven (0.25)	6.25	2	8.25
Construct PCB	Manufactured PCB (40.00), 4 LEDs (0.40), 1k potentiometer (0.95), LCD (5.99), button (0.50), fuse holder (0.78), 1N4001 diode (0.15), 0.15 µF capacitor (0.25), buzzer (7.89)	56.01	40	96.01
Add Flexsensor to Adhesive	soldered flex sensor (0.00), DuoDERM Extrathin Wound Dressing (1.40), electrical tape (negligable)	1.40	4	6.40
Manufacture Calibration Blocks	Cost for injection molding (9.06) Would be done from an outside source, since the equipment is too expensive to do in house given the small market size	9.06	0	9.06
Manufacture Microcontroller Casing	Cost for injection molding (31.25) Would be done from an outside source, since the equipment is too expensive to do in house given the small market size	31.25	0	31.25
Total Cost				**150.97**

5.4.4 High Scale Production:

Assume a $40.00 per hour labor cost for all calculations. Based on data from market analysis, assume a market size of 5,000 patients per year. Assume a 5 year lifespan for reusable components (arduino microcontroller, printed circuit board, hardware casing) for 1,000 units produced per year. Assume 5,000 units produced per year for all disposable components (flex sensor and adhesive).

Task	**Materials Required (cost)**	**Total Material Cost ($)**	**Labor Cost ($)**	**Total Cost ($)**
Solder Flex Sensor Wires	Flexs sensor (6.00), cost to run reflow oven (0.25)	6.25	2	8.25
Construct PCB	Manufactured PCB (40.00), 4 LEDs (0.40), 1k potentiometer (0.95), LCD (5.99), button (0.50), fuse holder (0.78), 1N4001 diode (0.15), 0.15 µF capacitor (0.25), buzzer (7.89), cost for SMT placement machine (16.00)	72.01	4	76.01
Add Flexsensor to Adhesive	soldered flex sensor (0.00), DuoDERM Extrathin Wound Dressing (1.40), electrical tape (negligable), cost to run machinery (0.25)	1.65	1	2.65
Manufacture Calibration Blocks	Cost for injection molding (9.06) Would be done from an outside source, since the equipment is too expensive to do in house given the small market size	9.06	0	9.06
Manufacture Microcontroller Casing	Cost for injection molding (31.25) Would be done from an outside source, since the equipment is too expensive to do in house given the small market size	31.25	0	31.25
Total Cost				**127.22**

6 Device Operation

Before opening the device, ensure that hands are thoroughly washed and the patient's head is clean, dry, and free of hair. The patient's head may be shaved if excessive hair is present so as to not interfere with device attachment.

The disposable adhesive and Flex Sensor of the device will be contained in a sterile package. The package should be carefully opened and the device can then be connected to the core Arduino module, as shown in **Figure 27**. Calibration can then begin as soon as the software is ready.

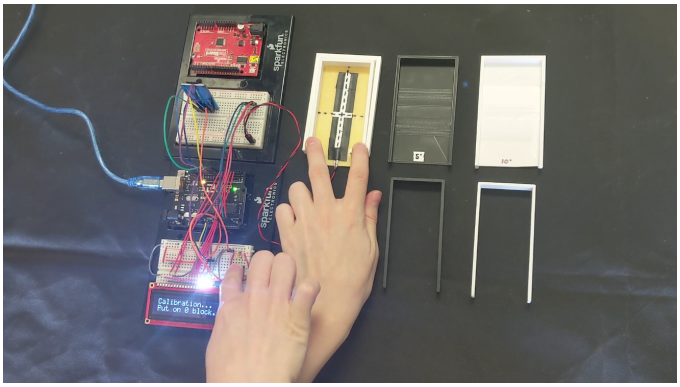

Figure 28: Plugging Flex Sensor to the Circuit Board

The device is calibrated by placing the adhesive with the Flex Sensor on top of the included calibration blocks. The device is first placed on the 0° block, secured by a separate piece, then a button on the user interface can be pressed to calibrate the device, as shown in **Figure 28**. The button needs to be held down until the white calibration LED lights up, indicating successful capture of data point.

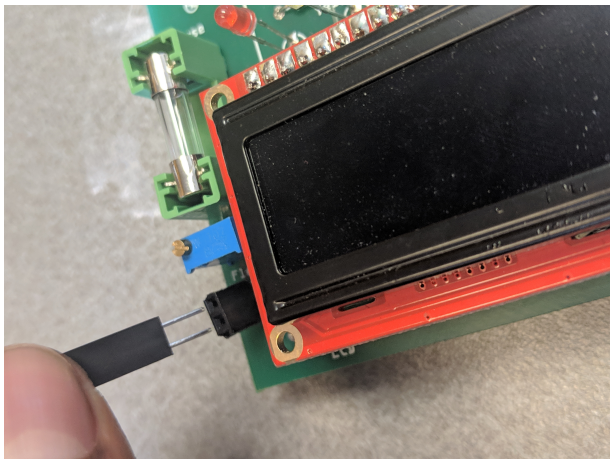

Figure 29: Placing the Device in Calibration Block and Pressing the Button Until Calibration LED Lights Up

Figure 30: Calibration Blocks

As soon as the software has completed this calibration, this process can be repeated for the 7° and 12° angle blocks, as shown in **Figure 29**. A similar button pressing process is used to account for the head curvature of the patient: the user presses down the button when the sensor is placed at the front and the back of the fontanelle, as shown in **Figure 30**. After these five points are taken, ICP is ready to be measured once the device is placed on the patient's head.

To place the device, carefully remove the top white paper on the adhesive. Align the cross drawn on the device with the approximate center of the anterior fontanelle, making sure the long side of the adhesive is parallel to the ear line, and gently apply the center part of the adhesive. Remove the bottom translucent paper on the adhesive while rolling the rest of the adhesive in place like a bandage without stretching the adhesive. Pat the adhesive down on the patient's head to ensure a firm attachment. Ensure the device is placed correctly. The process is shown in **Figure 31**.

To remove the device, first turn off the device and unplug the cables from the Arduino module. Then lift a corner of the adhesive and gently peel it back until it is completely removed from the patient's head. Wipe the patient's head with a sterile, wet cloth to remove any adhesive residue left behind. The Arduino module can be reused, while the Flex Sensor and adhesive casing can be disposed of.

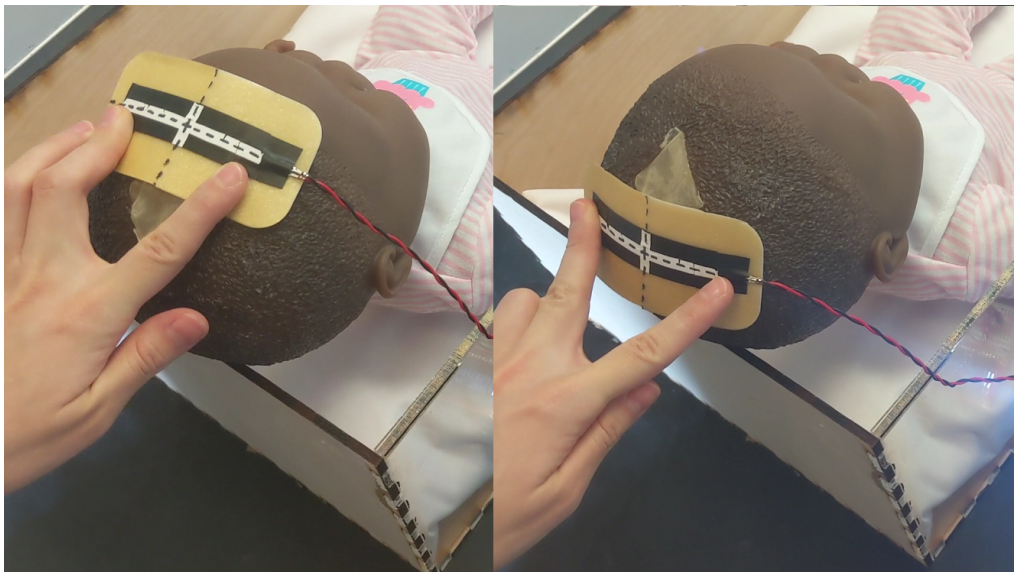

Figure 31: Calibration for Head Curvature. Left: Sensor at the Front of Fontanelle. Right: Sensor at the Back of Fontanelle.

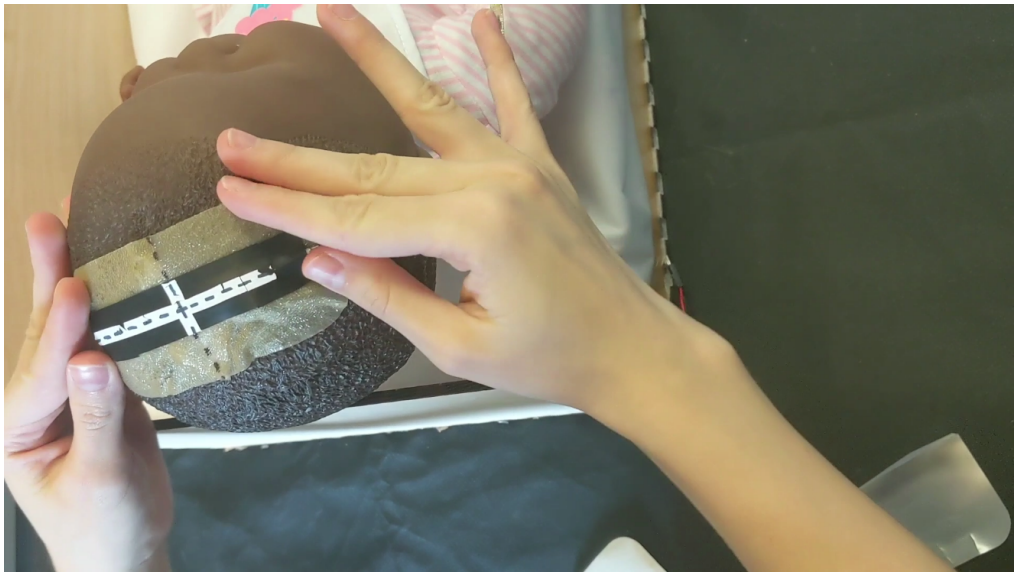

Figure 32: Attaching the sensor. Left: Matching the guide lines. Right: Patting down the adhesive.

The alarm system and the data storage system start working as soon as calibration is finished. When the entire measurement of ICP is completed (recommend a maximum length of 7 days), the SD card in the storage module can be taken out and placed into an SD card reader for access of the data, as shown in **Figure 32**.

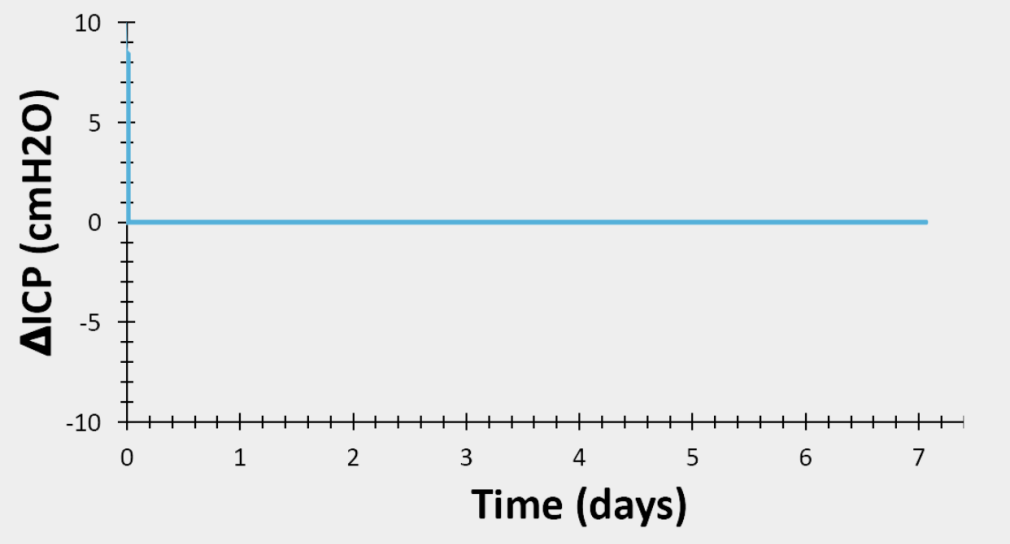

Figure 33: Plot of Error Versus Time for Zero Drift Testing of 7 Days

7 Device Implementation Plan

In order for our device to be placed onto the market, we must complete premarket requirements set by the U.S. Food and Drug Administration (FDA). These premarket requirement steps are listed below [38].

7.1 Premarket Requirements

7.1.1 Step 1: Classify Our Device

Every medical device is assigned a classification based on the degree of risk it presents. These classifications are defined in the **Code of Federal Regulations (CFR)**, and the classification determines the regulatory requirements for the device.

Our device is an **intracranial pressure (ICP) monitoring medical device**, and thus, must meet the FDA regulation, 21.CFR882.1620. This regulation classifies our device as a **Class II** device, and we must take into account the Class II general controls and special controls when designing and testing our device. The general controls provide the framework which the FDA uses to regulate devices and ensure their safety and effectiveness while the special controls are specific regulations for Class II devices for which general controls are insufficient in maintaining device safety and effectiveness [39].

In order to take all of these controls into account, we have detailed all of the necessary ones in our **Standards and Regulations** document, and we will address all of them in our premarket submission.

7.1.2 Step 2: Choose the Correct Premarket Submission

Since our device is a Class II device, we must complete a **Premarket Notification 510(k)**. This premarket submission requires our device to have a substantially-equivalent device that is currently legally-marketed in the U.S. The proposed device must be at least as safe and as effective as the substantial equivalent. There are ICP monitoring devices currently on the market such as the Integra® Camino® Intracranial Pressure Monitoring Kit that our clients use. We are currently in the process of consulting our clients and mentors about which one to specify as our substantially-equivalent device.

7.1.3 Step 3: Prepare the Appropriate Information for Our Premarket Submission to the FDA

While preparing our premarket submission, we must include information about our 1) **design controls**, 2) **nonclinical testing**, 3) **clinical evidence**, and 4) **labeling**.

The **design controls** are necessary to ensure that the device meets its specified design requirements. This process is detailed in the Quality Systems regulation, 21.CFR.820.30 as well as the Quality Management Systems standard, ISO 9000. We must follow both of these when documenting our design controls in the premarket submission. The design controls themselves involve the following:

1. Identifying and understanding user needs

2. Establishing the functions of the device
3. Establishing design specifications and target goals
4. Validation (testing to determine if our device meets these goals)

We have already completed parts one, two, and three by:

1. Defining our customer needs in our Product Development Worksheet
2. Creating a functional decomposition for our device as shown in Figure 1 of the Design Specifications section
3. Defining our design specifications and target goals (**Table 2**)

In order to complete the validation portion of the design controls, we are currently in the process of developing testing methods to ensure that our device meets our design specification targets (**Table 2**). We will consult the American Society for Testing and Materials (ASTM) for testing procedures similar to our needs and will refine our testing methods based on these [40]. We will then apply for Institutional Review Board (IRB) approval to conduct testing and will do so after receiving approval.

For the **nonclinical testing** of our device, we must comply with the Good Laboratory Practices (GLPs) detailed in 21.CFR.58. We are currently refining our testing plans to meet this regulation, and this testing includes our:

1. Accuracy testing on a nonclinical model
2. Frequency of measurements/time delay testing
3. Time for operation testing
4. Maximum time for monitoring testing
5. Degree of invasiveness survey

We do not need to complete an IRB application for the first four tests, but we do need to complete an IRB application for our degree of invasiveness survey in order to survey legal guardians of the patients.

Once we have a final prototype, we will also need to conduct **clinical testing** to test our device against our design specifications and to make sure the device functions as expected. In the future, we will further refine our accuracy testing method for a clinical setting while still complying with Good Clinical Practices (GCPs). We must also obtain IRB approval as well as Investigational Device Exemption (IDE) before performing these tests.

The **labeling** that we will eventually have on our device must also be included in our premarket submission. We plan to create this labeling in accordance to the labeling regulations detailed in 21.CFR.801.

7.1.4 Step 4: Send Premarket Submission to the FDA

After compiling all of the sections of the 510(k) Premarket Notification, we will send our submission to the FDA for review. To do so, we will have to pay the user fee of $10,953 (the standard fee) [41]. We will also have to include an eCopy of our submission on a compact disc (CD), a digital video disc (DVD), or a flash drive.

Once the FDA receives the premarket submission, they will conduct an **Acceptance Review** to assess whether or not the submission passes the **Acceptance Checklist** in the document titled, "**Refuse to Accept Policy for 510(k)s** [42]." This checklist includes questions about eligibility, if there are similar devices currently being reviewed, if our device has clinical data, etc. Once the submission passes the acceptance review, it will move on to the **Substantive Review**. During the substantive review, the FDA lead reviewer will conduct a comprehensive review of the submission, and if there are any issues to address, they will enact a **Substantive Interaction**. This substantive interaction is typically an email that requests additional information or requires actions to address significant deficiencies in the submission. The final decision for a 510(k) should be given within 90 days, and it will come in the form of a decision letter sent via email. However, we extended this period to be 180 days to account for possibility of multiple correspondence, which may lead to delayed return of the final decision. The timeline for a 510(k) review is also shown in **Figure 33**.

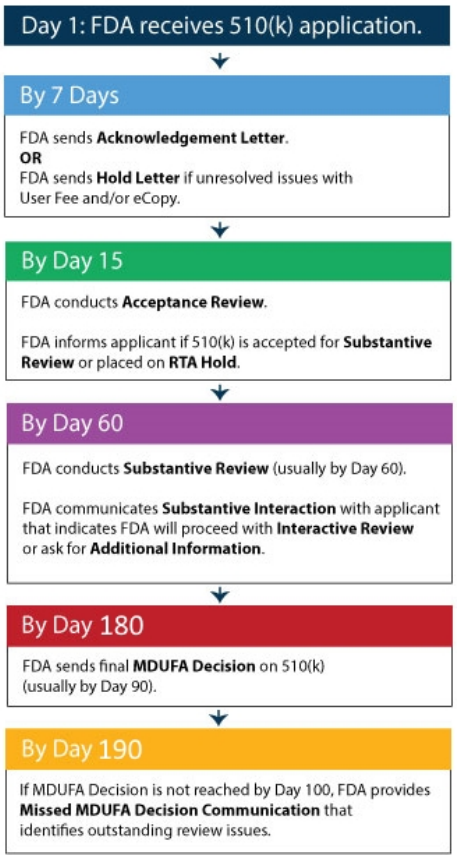

Figure 34: Timeline for FDA 510(k) Review [42]

7.1.5 Step 5: Complete the Establishment Registration and Device Listing

After receiving FDA approval from the 510(k) Premarket Notification, we can then register our establishment and list our device with the FDA as per regulation 21.CFR.807. There is an annual registration user fee that we will need to pay in order to keep our device listed as a medical device in the United States. The fee changes annually and is $4,884 for the fiscal year of 2019 [43]. Once we complete registration and listing, we can then move onto the manufacturing, commercialization, and implementation of our medical device.

8 Standards and Regulations

Our device is categorized as an **intracranial pressure (ICP) monitoring medical device** and must therefore comply with all relevant international requirements, including those from the International Organization for Standardization (ISO) and the Association for the Advancement of Medical Instrumentation (AAMI). Additionally, the device must comply with the U.S. Food and Drug Administration (FDA) requirements. These requirements are in the form of standards (listed in **Table 9**) and regulations (listed in **Table 10**).

Table 9: List of Standards Applicable for our Device

Number	Title
ISO 13485:2016	Medical Devices: Quality Management System: Requirements For Regulatory Purposes
ISO 14971:2007	Medical Devices: Application of Risk Management To Medical Devices
ISO 10993-11:2017	Biological Evaluation of Medical Devices
AAMI NS28:2015	Intracranial Pressure Monitoring Devices
IEC 60601-1-11:2015	Medical Electrical Equipment
IEEE 11073-20702:2018	Point of Care Medical Device Communication

Table 10: List of Regulations Applicable for our Device

	Number	Title
Device Specific	**21CFR882.1620**	Intracranial pressure monitoring device
General Controls	**FD&C Act Sec. 501(21CFR803)**	Adulterated drugs and devices
	FD&C Act Sec. 502(21CFR801)	Misbranded drugs and devices
	FD&C Act Sec. 510(21CFR807)	Registration of producers of drugs or devices
	FD&C Act Sec. 516(21CFR895)	Banned devices
	FD&C Act Sec. 518(21CFR1003)	Notification and other remedies
	FD&C Act Sec. 519(21CFR803/806)	Records and reports on devices
	FD&C Act Sec. 520	General provisions respecting control of devices intended for human use
	FD&C Act Sec. 520(21CFR820)	Quality system regulation
Special Controls	**FD&C Act Sec. 513(21CFR860)**	Medical device classification procedures
	FD&C Act Sec. 514(21CFR861)	Performance standards
	FD&C Act Sec. 522(21CFR822)	Postmarket surveillance

8.1 Standards

8.1.1 ISO 13485:2016

ISO 13485:2016 specifies requirements for a quality management system where an organization needs to demonstrate its ability to provide medical devices and related services that consistently meet customer and applicable regulatory requirements [44].

8.1.2 ISO 14971:2007

ISO 14971:2007 specifies a process for a manufacturer to identify the hazards associated with medical devices, including *in vitro* diagnostic (IVD) medical devices, to estimate and evaluate the associated risks, to control these risks, and to monitor the effectiveness of the controls. The requirements of ISO 14971:2007 are applicable to all stages of the life-cycle of a medical device [45].

8.1.3 ISO 10993-11:2017

This document specifies requirements and gives guidance on procedures to be followed in the evaluation of the potential for medical device materials to cause adverse systemic reactions [46].

8.1.4 AAMI NS28:2015

This standard establishes minimum labeling, safety, and performance requirements for intracranial pressure monitoring devices, whether percutaneous, fully implantable, or noninvasive. Also covered by this standard are test and calibration methods needed to establish compliance with the standard [47].

8.1.5 IEC 60601-1-11:2015

This standard applies to the basic safety and essential performance of medical electrical equipment and medical electrical systems for use in the home healthcare environment. It applies regardless of whether the medical electrical equipment or medical electrical system is intended for use by a lay operator or by a trained healthcare personnel [48].

8.1.6 IEEE 11073-20702:2018

This standard specifies a communication protocol for a distributed system of point of care medical devices and medical IT that needs to exchange data [49].

8.2 Regulations

8.2.1 21CFR882.1620: Intracranial pressure monitoring device

This regulation classifies an intracranial pressure (ICP) monitoring device as a Class II device. Since our device falls under the classification of an ICP monitor, we must take into account the **Class II general controls** and **special controls** when designing and testing our device [40].

General Controls:

General controls provide the framework which the FDA uses to regulate devices and ensure their safety and effectiveness [39]. **General controls** for our device consist of the following sections of the **Federal Food, Drug, and Cosmetic** (FD&C) Act and the **Code of Federal Regulations** (CFR) [50]:

- FD&C Act Sec. 501 (21CFR803) - Adulterated drugs and devices
- FD&C Act Sec. 502 (21CFR801) - Misbranded drugs and devices
- FD&C Act Sec. 510 (21CFR807) - Registration of producers of drugs or devices
- FD&C Act Sec. 516 (21CFR895) - Banned devices
- FD&C Act Sec. 518 (21CFR1003) - Notification and other remedies
- FD&C Act Sec. 519 (21CFR803/806) - Records and reports on devices
- FD&C Act Sec. 520 - General provisions respecting control of devices intended for human use
  - FD&C Act Sec. 520 (21CFR820) - Quality system regulation

8.2.2 FD&C Act Sec. 501; 21CFR803: Adulterated drugs and devices

This regulation ensures that our device will not contain any parts or components that are contaminated/dangerous to the patient's health. Additionally, our device must not have been manufactured or prepared under insanitary or hazardous conditions. The quality of the product must consistently meet the standards and requirements that it is subject to.

8.2.3 FD&C Act Sec. 502; 21CFR801: Misbranded drugs and devices

This regulation ensures that our device will not contain any false or misleading labeling. The package of the device must have a label that identifies 1) the name and place of the manufacturer/packer/distributor and 2) the quantity of the contents. The labeling must be displayed prominently enough for an individual to be able to notice and read it.

8.2.4 FD&C Act Sec. 510; 21CFR807: Registration of producers of drugs or devices

This regulation details the registration procedures that the producers of our device must complete. This process includes: 1) business/establishment registration 2) list of devices with established performance standards, and 3) Premarket Notification 510(k).

The **Premarket Notification 510(k)** requires the proposed device to have a substantially equivalent device that is currently a legally U.S. marketed device. The proposed device must be at least as safe and as effective as the substantial equivalent.

8.2.5 FD&C Act Sec. 516; 21CFR895: Banned devices

This regulation ensures that if our device puts people at unreasonable risk of illness or injury, then the device can be banned. If our device has this unreasonable risk of illness or injury but can be corrected or eliminated with labeling, then the manufacturer can provide a written notice to incorporate this labeling and avoid a ban on the device.

8.2.6 FD&C Act Sec. 518; 21CFR1003: Notification and other remedies

This regulation ensures that if our device presents an unreasonable risk of illness or injury and if there are no other ways to eliminate the risk, then there must be notification about the risk to all involved individuals in order to mitigate this risk. If our device presents a risk that was not due to manufacturer, distributor, or retailer failure and that would not be eliminated with a notification, then our device must have a plan to assure that the risk will be eliminated via repair, replacement, refund, or recall.

8.2.7 FD&C Act Sec. 519; 21CFR803/806: Records and reports on devices

This regulation ensures that the manufacturer or importer of our device will establish and maintain records for the device relating to 1) cause of serious injury and/or death, 2) malfunction, 3) assurance that the device is not adulterated, 4) assurance that the device is not misbranded, and 5) assurance of the device's safety and effectiveness.

8.2.8 FD&C Act Sec. 520: General provisions respecting control of devices intended for human use

This regulation ensures that devices intended for human use must follow sections 501, 502, 510, and 519 from the FD&C Act. This regulation also describes the practices related to custom devices,

restricted devices, good manufacturing practice requirements, exemptions for devices for investigational use, transitional provisions for devices considered as new drugs, humanitarian drug exemption, and the establishment and regulation of proper quality systems (21CFR820).

Special Controls:

Special controls are specific regulations for Class II devices for which general controls are insufficient in maintaining device safety and effectiveness [51]. **Special controls** for our device include the following regulations [50]:

- FD&C Act Sec. 513 (21CFR860) - Medical device classification procedures
  - Patient registries
  - Special labeling requirements
  - Premarket data requirements
  - Guidelines
- FD&C Act Sec. 514 (21CFR861) - Performance standards
- FD&C Act Sec. 522 (21CFR822) - Postmarket surveillance

These regulations will be described in detail in the following sections.

8.2.9 FD&C Act Sec. 513; 21CFR860: Medical device classification procedures

This regulation categorizes our device into its proper classification and describes the regulations that pertain to its classification. Since our device is a Class II device, it states that our device will be subject to general controls as well as special controls such as the ones that have been described in this document.

8.2.10 FD&C Act Sec. 514; 21CFR861: Performance standards

This regulation ensures that our device will have established performance standards that prove the function and performance of the device through proper manufacturing processes, testing, and labeling.

8.2.11 FD&C Act Sec. 522; 21CFR822: Postmarket surveillance

Since our device has the potential to cause serious injury or illness due to failure, this regulation ensures that our device will be monitored after launch in order to predict or quickly realize adverse events occurring due to use of the device.

8.3 Impact on Our Device

Moving forward, we will inspect these standards and regulations in greater detail to ensure our understanding of the requirements that they outline. We will conduct testing and quality control to determine if our device is compliant with the necessary criteria. Furthermore, we will discuss these standards and regulations with our clients to gauge professional input with regards to ensuring the utility and safety of our device.

9 Testing Plans and Results

Our team conducted a series of test to determine if our device met each of our design specification. We conducted some tests several times to reevaluate our device as our prototype and testing methods improved.

9.1 Accuracy and Time Delay Testing

The first series of tests conducted were to determine the accuracy and time delay of the device with a final goal of an accuracy of ± 5 cmH_2O compared to predicted ICP and a time delay of less than 5 minutes, respectively. We accomplished this using an apparatus to bend our device and calculated the difference between the ICP measured by the device compared to predicted values. Accuracy and time delay were tested simultaneously because of the similarities in experimental procedure between the two tests. These tests were performed 3 times.

9.1.1 Test 1: Model Fontanelle as Standards

9.1.1.1 Equipment Used

- Fontanelle model: We made our first fontanelle model using a Dixie EMS Black Deluxe Aneroid Sphygmomanometer, which is able to inflate in a similar way to a fontanelle due to applied pressure inside it, as shown in **Figure 34**. The model was shaped and secured into a rough fontanelle shape using duct tape so as only the fontanelle-shaped portion would inflate.
- Device: When conducting this test, we had not yet developed an attachment method, so testing was conducted using the flex sensor alone.
- Stopwatch: Used to test for time delay.

9.1.1.2 Testing Instructions

1. Place device on fontanelle model.
2. Inflate fontanelle model to a gauge pressure of 1.36 cmH_2O.
3. Record the ICP measured by device.
4. Use a stopwatch to measure the time between inflating the fontanelle model and the reading on the LCD stabilizing and record this value.
5. Repeat steps 2-4 for pressures between 2.72 cmH_2O and 68 cmH_2O in 1.36 cmH_2O increments.

9.1.1.3 Data Analysis and Statistical Techniques

The expected ICP in the fontanelle model based on the gauge pressure in the model will be compared to the average of the measured ICP by our device at each pressure recorded using a t-test for independent samples assuming equal variance with α = 0.05.

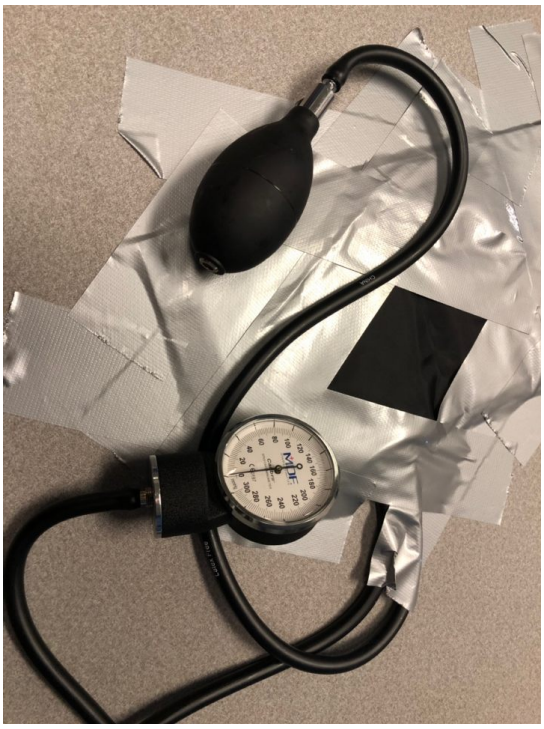

Figure 35: Sphygmomanometer used for accuracy testing.

The average time delay will be tested for whether or not it is statistically less than our expected goal (5 minutes) using a t-test for independent samples assuming equal variances with α = 0.05.

9.1.1.4 Acceptance Criteria

The device will pass the accuracy test if it can measure ICP within ± 10 cmH_2O of the model's gauge pressure based on literature values.

Our time delay test will be successful if measurements are displayed within 5 minutes of detection.

9.1.1.5 Testing Results

A graph summarizing the results for the accuracy test are shown in **Figure 35**. The device was accurate within ± 10 cmH_2O for all ICP values measured. In addition, the device was accurate within ± 5 cmH_2O for all ICP values greater than 15 cmH_2O, which is our final target accuracy.

The average time delay for our device was found to be 2.81 ± 0.30 seconds, meaning that we met our target for time delay

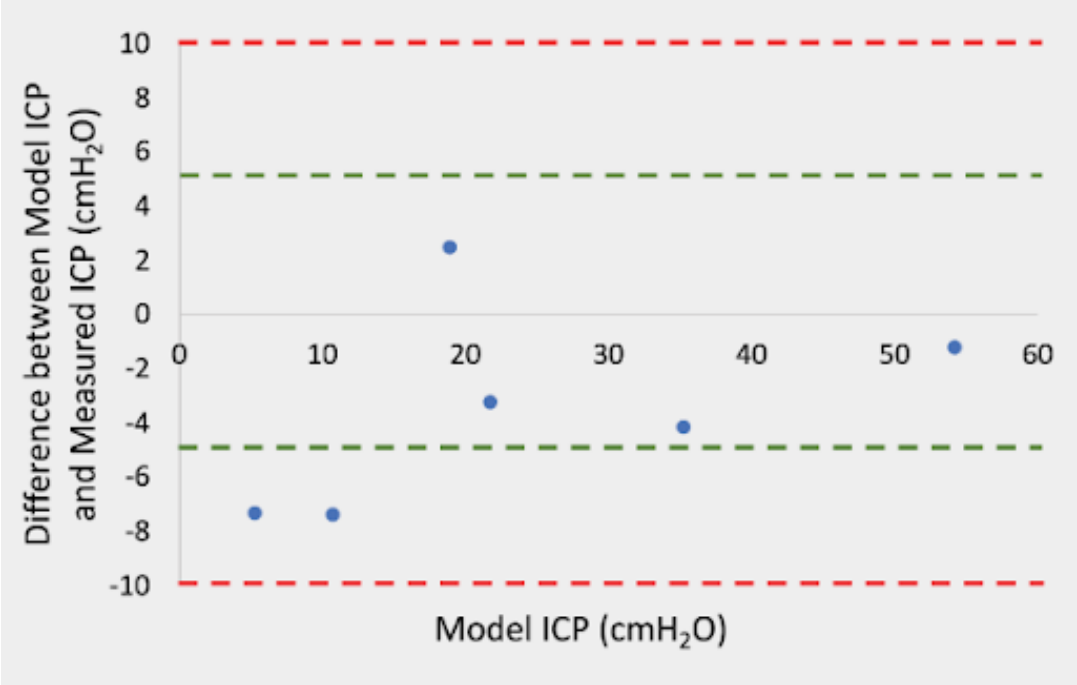

Figure 36: Graph of data for first round of accuracy testing.

9.1.2 Test 2: Calibration Blocks as Standards

9.1.2.1 Equipment Used

- Initial Calibration Blocks.
- Test Blocks: Wooden blocks similar to initial calibration blocks. Manufactured using laser cutting and able to bend device at angles between 0° and 12°.
- Device: For this test, attachment method 1 was used.
- Stopwatch: Used to test for time delay.

9.1.2.2 Testing Instructions

1. Calibrate device as per instruction manual using initial calibration method.
2. Place device on 0° test block.
3. Record the ICP measured by device.
4. Use a stopwatch to measure the time between placing device on test block and the reading on the LCD stabilizing and record this value.
5. Repeat steps 2-4 for remaining test blocks (angles 1°-12°).
6. Repeat steps 1-5 three times for repeatability.

9.1.2.3 Data Analysis and Statistical Techniques

The expected ICP in the test blocks based on literature values at the flexion angles recorded will be compared to the average of the measured ICP by our device at angle recorded using a t-test for independent samples assuming equal variance with α = 0.05.

The average time delay will be tested for whether or not it is statistically less than our expected goal (10 seconds) using a t-test for independent samples assuming equal variances with α = 0.05.

9.1.2.4 Acceptance Criteria

The device will pass the accuracy test if it can measure ICP within ± 5 cmH_2O of expected pressure based on literature values.

Our time delay test will be successful if measurements are displayed within 10 seconds of detection.

9.1.2.5 Testing Results

The accuracy and time delay values for each angle tested are summarized in **Table 11**. The data indicate that the device remained accurate within ± 6 cmH_2O for all angles, meaning that we did not meet our target accuracy.

The time delay data show that the average time delay was less than two seconds for all angles, meaning that we met our target for time delay.

Table 11: Accuracy and Time Delay Data for Test 2

Angle (Degrees)	Average Measured ICP (cm$H_2$0)	Predicted ICP (cm$H_2$0)	Difference (cm$H_2$0)	Accuracy SD (cm$H_2$0)	TD Average (Seconds)	TD SD (Seconds)
0	2.81	-0.0423	2.86	0.641	0.848	0.294
1	4.95	3.462	1.48	0.824	1.018	0.509
2	7.01	6.1053	0.90	0.586	1.018	0.509
3	11.01	8.181	2.83	0.959	0.679	0.294
4	13.00	9.9825	3.01	0.760	1.018	0.509
5	10.9	11.8032	-0.90	1.11	1.018	0.509
6	14.44	13.9365	0.50	0.987	1.188	0.294
7	22.13	16.6758	5.46	3.900	0.848	0.294
8	22.96	20.3145	2.65	1.887	1.357	0.294
9	30.65	25.146	5.50	2.936	1.357	0.294
10	33.77	31.4637	2.31	3.301	1.357	0.294
11	42.63	39.561	3.06	1.370	1.357	0.294
12	45.74	49.7313	-3.99	2.186	1.527	0

9.1.3 Test 3: Refined Calibration Blocks as Standards

9.1.3.1 Equipment Used

- Iterated Calibration Blocks.
- Test Blocks: Manufactured using 3D printing and able to bend device at 0° angles as well as angles between 5° and 12° in 1° increments.
- Device: For this test, attachment method 1 was used.

- Computer Running Accuracy Testing Code: We modified our normal code for use in accuracy and time delay testing. The code would output the measured ICP as well as elapsed time from completion of calibration on the serial monitor. This was used for measuring time delay.

9.1.3.2 Testing Instructions

1. Complete steps 1-3 of the calibration process as per the instruction manual.
2. When instructed to place the device on the front or back of the fontanelle, instead repeat step 1 of the calibration process (placing device on 0° calibration block).
3. Place device on 0° test block.
4. Record the ICP measured by device.
5. Use serial monitor to determine elapsed time between placing the device on the test block and the reading stabilizing and record this value.
6. Repeat steps 2-4 for remaining test blocks (angles 5°-12°).
7. Repeat steps 1-5 three times for repeatability.

9.1.3.3 Data Analysis and Statistical Techniques

The expected ICP in the test blocks based on literature values at the flexion angles recorded will be compared to the average of the measured ICP by our device at angle recorded using a t-test for independent samples assuming equal variance with α = 0.05.

The average time delay will be tested for whether or not it is statistically less than our expected goal (10 seconds) using a t-test for independent samples assuming equal variances with α = 0.05.

9.1.3.4 Acceptance Criteria

The device will pass the accuracy test if it can measure ICP within ± 5 cmH_2O of expected pressure based on literature values.

Our time delay test will be successful if measurements are displayed within 10 seconds of detection.

9.1.3.5 Testing Results

The accuracy and time delay values for each angle tested are summarized in **Table 12**. The data indicate that the device remained accurate within ± 6 cmH_2O for all angles, meaning that we did not meet our target accuracy.

The time delay data show that the average time delay was less than two seconds for all angles, meaning that we met our target for time delay.

Table 12: Accuracy and Time Delay Results for Test 3

Angle (Degrees)	Average Measured ICP (cmH_20)	Predicted ICP (cmH_20)	Difference (cmH_20)	Accuracy SD (cmH_20)	TD Average (Seconds)	TD SD (Seconds)
0	0.277	-0.042	0.319	2.876	2.361	0.292
5	5.1	11.803	-6.704	0.181	2.361	0.773
6	9.519	13.937	-4.417	1.198	1.518	0.506
7	10.258	16.676	-6.418	1.058	2.53	0.506
8	16.713	20.315	-3.601	2.598	1.518	0.506
9	26.71	25.146	1.564	2.666	3.88	0.585
10	31.767	31.464	0.303	3.668	3.374	1.274
11	44.297	39.561	4.736	7.809	2.867	1.627
12	46.82	49.731	-2.911	0.718	2.53	0

9.2 Change in Accuracy Due to Position

When determining the most appropriate attachment method for our device, we drafted the following test to measure the change in accuracy of the device at different points in the fontanelle. This was important for attachment method 2 because of concerns of the device shifting overtime, which may affect ICP readings. We decided to focus on attachment method 1 before conducting this test.

9.2.1 Equipment Used

- Baby testing model (Figure 36) : this model was created by cutting an anterior fontanelle shape on a 20” length baby doll (Lakeshore Learning Item # DS802). The fontanelle shape is 6 cm long and 2.5 cm wide, and was placed by measuring the intersection of the line connecting the back of each of the doll’s ears and the line along the dorsum of the nose to the back of the head. This intersection was marked as the middle of the fontanelle, and a diamond shape was cut along the doll’s head. A piece of elastic material (36" clear balloon B07F8Q33M8) was then attached flush with the skin from the outside to simulate skin on the fontanelle. An interior pressure modulating component was created by attaching a water pressure sensor (SEN0257) to a balloon and (36" clear balloon B07F8Q33M8) a water pump (Adafruit Product ID 3910) to the same balloon. The water pump was connected with tubing to a glass of water to fill the balloon. The pressure sensor and the water pump were then attached to a breadboard circuit designed to pump water in or out of the balloon given a desired pressure inside of said balloon. The circuit was then connected to Arduino for user control of desired pressure. It is important to note that the elasticity of the balloon is different from the skin elasticity on the fontanelle. Measuring calculated pressure vs. applied water pressure would thus lead to inaccurate testing. Despite this, the balloon is able to inflate to a similar shape to the fontanelle at different pressures and will be used as a model to vary the degree of flexion (angle achieved by inflating the balloon) of the fontanelle.
- Calipers.
- Device.
- Calibration Package.
- Location Guide (**Figure 37**).

9.2.2 Testing Instructions

1. Calibrate the device as per instruction manual.

Figure 37: Baby head model used as a testing model

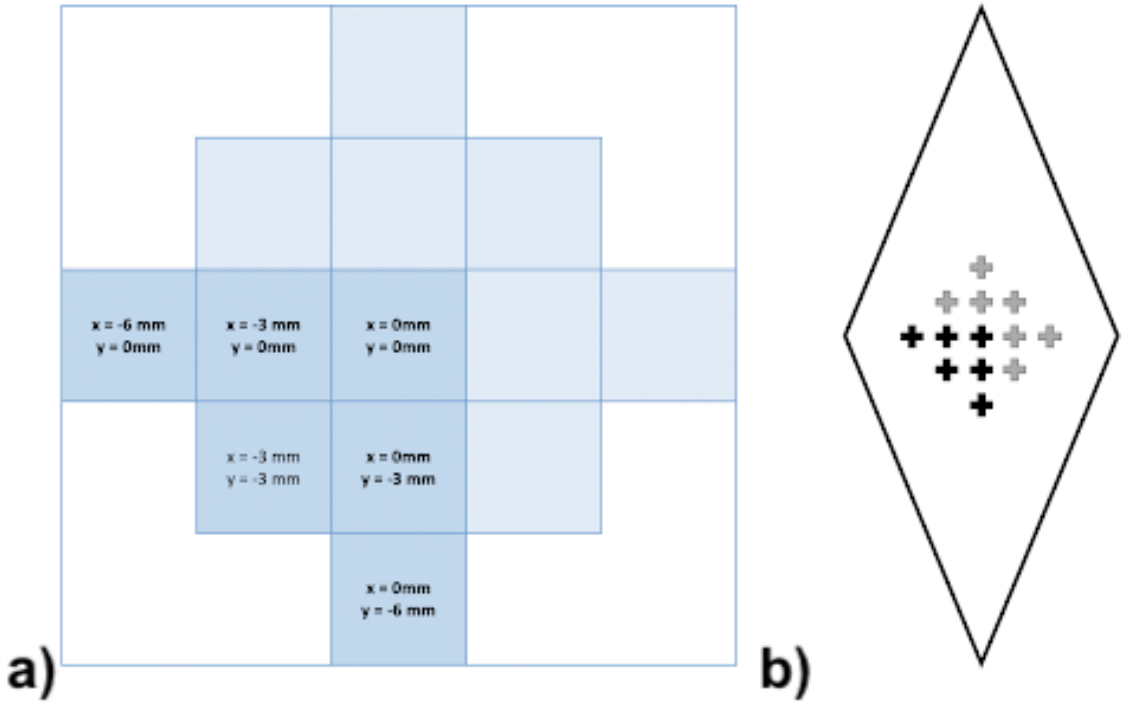

Figure 38: Guide of locations to measure to determine effect of sensor placement on accuracy

2. Place the device on the baby model's head as per instruction manual, placing the x mark on the center of the fontanelle.
3. Turn on baby model and inflate the device to approximately 0°. Confirm the angle of the fontanelle flexion with calipers.
4. Record ICP at center of fontanelle.
5. Move Flex Sensor 3mm in positive x direction and record ICP.
6. Repeat step 5 until ICP reading is no longer within ± 5 cmH_2O of the ICP reading at the center of the fontanelle.
7. Repeat steps 5 and 6 starting from the center of the fontanelle, but move the Flex Sensor in the positive y direction.
8. Inflate the device in 2° increments and repeat steps 4-7. Data should be recorded from 0° to 10° (correlating to 0 to 31.5 cmH_2O).
9. Turn off device and baby model.
10. Repeat steps 1 to 9 three times for repeatability.

9.2.3 Data Analysis and Statistical Techniques

The expected ICP in the baby head based on literature values [34] at the flexion angles recorded will be compared to the average of the measured ICP by our device at each angle recorded using a t-test for independent samples assuming equal variances with α = 0.05. Data can also be plotted to extrapolate the exact x and y position where our device would reach unacceptable accuracy criteria. This is not necessary however.

9.2.4 Acceptance Criteria

The point where the accuracy exceeds the accepted error ± 5 cmH_2O) will be used as a number for maximum allowed displacement in both the x- and y- displacement. This test is purely exploratory to get a number for maximum displacement.

9.3 Attachment Method Ease of Use Testing:

In order to determine which of our two attachment methods we should proceed with, we conducted a test to gauge how easy each attachment method was to use.

9.3.1 Equipment Used

- Initial Calibration Blocks.
- Baby Doll: Lakeshore Learning Item # DS802.
- Device: For this test, the sensor was bare.
- Adhesive Packaging: Duoderm CGF Extra Thin Sterile Dressing.
- Stopwatch.

9.3.2 Testing Instructions

1. Set up testing environment by placing the baby doll in its crib, attaching the flex sensor to the computer, setting the calibration package, and setting packages of adhesives next to the computer.

2. Get testing subjects from different groups: our team (n = 5), Rice students (at least n = 10), and medical professionals (at least n = 10). We chose these numbers as we don't have *a priori* knowledge on variability between respondents to conduct power analysis, but we wanted to have as many respondents as possible to achieve statistical significance.

3. Give testing subjects verbal instructions as well as a demonstration on proper use of the device. They will be instructed to remove the adhesive from the sterile packaging, place the device on top of the adhesive, calibrate the device, and place the device on top of the baby's head as shown in the video.

4. Instruct testing subjects to start the test. Record time with the stopwatch from the moment they touch the adhesive package to the moment they take their hands off the baby doll after placing the device.

5. Repeat steps 2-3 for attachment method 2.

9.3.3 Data Analysis and Statistical Techniques

The average time for operation for each attachment method will be compared using a paired t-test assuming equal variances with α= 0.05. If the difference of average attachment time is statistically significant, we will proceed with the method with the smaller average operation time.

9.3.4 Testing Results

The results for this test are shown below in **Table 13**. These results indicate that attachment method 2 takes a significantly longer amount of time to perform. As a result, we continued ot iterate using attachment method 1.

Table 13: Comparison Between Operation Times for Attachment Methods 1 and 2

	Time for Operation (Seconds)	
Operator	**Attachment Method 1**	**Attachment Method 2**
1	53.95	68.7
2	59.38	96.34
3	71.91	142.33
4	108.22	122.93
5	64.39	152.31
Average	71.57	116.52
Standard Deviation	21.52	34.21

9.4 Time for Operation:

Our goal is to test how much time it would take the average device user to set up and put on the device. This test was conducted twice. Any differences between the two times this test was conducted will be noted:

9.4.1 Equipment Used

- Calibration Blocks: for test 1, initial calibration blocks were used, for test 2, iterated calibration blocks were used.
- Baby Doll: Lakeshore Learning Item # DS802.
- Device: For this test, the sensor was bare.
- Adhesive Packaging: Duoderm CGF Extra Thin Sterile Dressing.
- Stopwatch.

9.4.2 Testing Instructions

1. Set up testing environment by placing the baby doll in its crib, attaching the flex sensor to the computer, setting the calibration package, and setting packages of adhesives next to the computer.
2. Get testing subjects from different groups: our team (n = 5), Rice students (at least n = 10), and medical professionals (at least n = 10). We chose these numbers as we don't have *a priori* knowledge on variability between respondents to conduct power analysis, but we wanted to have as many respondents as possible to achieve statistical significance.
3. Give testing subjects verbal instructions as well as a demonstration on proper use of the device. They will be instructed to remove the adhesive from the sterile packaging, place the device on top of the adhesive, calibrate the device, and place the device on top of the baby's head as shown in the video.
4. Instruct testing subjects to start the test. Record time with the stopwatch from the moment they touch the adhesive package to the moment they take their hands off the baby doll after placing the device.
5. After the device is placed, determine whether the user was able to do the following:
   (a) Calibrate the device properly.
   (b) Attach the device in the correct orientation on the fontanelle.
   (c) Attach the device so the flex sensor center matches the center of the fontanelle.

9.4.3 Data Analysis and Statistical Techniques

The average time for operation for each testing group will be tested for whether or not it is statistically less than our expected goal (30 minutes) using a t-test for independent samples assuming equal variances with $\alpha = 0.05$.

9.4.4 Acceptance Criteria

The device will pass the test if the average time to place the device is less than 30 minutes.

9.4.5 Testing Results

For both tests, the time for operation was less than our target value. The results for test 1 are shown in **Table 14** and the results for test 2 are shown in **Table 15**.

Table 14: Time for Operation Testing for Test 1

Participant	Time for Operation (Seconds)	Average (Seconds)	Standard Deviation (Seconds)
1	51.7	55.3	25.9
2	114		
3	91.2		
4	49.6		
5	34.4		
6	36.4		
7	38.1		
8	35.1		
9	45.0		
10	44.6		
11	67.2		

Table 15: Time for Operation Testing for Test 2

Participant	Time for Operation (Seconds)	Average (Seconds)	Standard Deviation (Seconds)
1	77.17	72.0	12.8
2	95.53		
3	79.43		
4	83.21		
5	76.77		
6	59.11		
7	70.49		
8	65.19		
9	59.89		
10	53.83		

9.5 Electrical Safety:

This test will be conducted to ensure that the electrical components of our device will not pose a safety hazard.

9.5.1 Equipment Used

- Device: for this test, attachment method 1 is used.
- Digital Multimeter (DMM).

9.5.2 Testing Instructions

1. Inspect all electrical components of device to ensure that the circuitry is identical with the circuitry in our circuit diagram. This consists of the following steps:
   (a) Confirming all resistors used have the correct resistance using both the digital multimeter (DMM) and resistor color codes.
   (b) Confirming that all components are wired in the correct location and with correct polarity, if applicable.
   (c) Confirming proper connections, both between electrical components and between components and ground.
   (d) Replacing any damaged or missing components. This includes frayed wires, components with missing insulation, or burnt fuses.
2. The resistance of the protective casing of the circuit (the Duoderm adhesive covering the Flex Sensor as well as the casing surrounding the circuitry) will be measured by applying 500 V.

9.5.3 Data Analysis and Statistical Techniques

Because this test only gives binary results, this test does not require any statistical analysis.

9.5.4 Acceptance Criteria

Our device will pass the test following inspection of all components and replacement of any damaged or miswired components.

9.6 Patient Comfort Testing:

Our goal is to ensure that our device does not cause significant pain or discomfort to our target patient population when in use to ensure quality of treatment and minimal loss of accuracy that may occur due to patient movement.

9.6.1 Equipment Used

- Sterile Gloves.
- Video recording equipment (video camera).
- Two people: one to record, one to place the device.

9.6.2 Testing Instructions

1. Gather at least 10 infants aged 18 months old or less. As before, we do not know *a priori* the variability between patients, but for this pilot study we wanted to have as many infants to test as possible.
2. The person attaching the device should prepare to touch the baby by thoroughly washing hands and putting on sterile gloves as per the TCH neonatal ICU protocol.
3. Begin recording the testing subject for a 5 minutes before the device is placed to establish baseline comfort level.

4. Attach the device on each testing subject as per user manual. As we are only concerned with patient comfort, the device need not be turned on or calibrated for this test.

5. Leave the device on the testing subject for 20 min, then remove the device from the testing subject. End video recording a few minutes after device removal.

6. Repeat steps 2-5 for all testing subjects.

9.6.3 Data Analysis and Statistical Techniques

The recorded videos will be randomized in order and distributed to at least 5 parents of one child aged 2 years or younger, 5 parents of two or more children with at least one aged 2 years or younger, and 5 neonatal ICU nurses with no prior knowledge of our device. This would give us an n = 15 for all groups and an n = 5 for each group. We chose these numbers as we had no *a priori* knowledge of the variance of comfort diagnosis between subjects, and we wanted to have as many data points as is reasonably possible to have statistical significance. Each subject will be asked to observe the videos and gauge patient comfort at 5 time points: prior to the device attachment, during device attachment, 20 minutes after device attachment, during device removal, and after device removal. The data collected immediately prior to attachment will be used as a baseline for comparison of the comfort level for the other three conditions.

We will quantify patient comfort using a modified COMFORT scale, shown in **Figure 38**. The COMFORT scale is used to gauge sedation levels in children based on multiple criteria, each given a score between one and five. We will use the same scale to gauge comfort levels, but will not measure respirator response or muscle tone, for these criteria are only relevant for patients under sedation. At each of the time points described above, we will observe the patient and assign a number between one and five for the six remaining criteria: alertness, calmness/agitation, physical movement, blood pressure (MAP), heart rate, and facial expression. For each time point, we will average the scores for each criteria and use the ANOVA to judge whether each group's perceived patient comfort is within one point of the initial comfort level for patients (before device is attached).

9.6.4 Acceptance Criteria

Our device will pass the test if the averages for the during device attachment, 20 minutes after attachment, and during device removal time points are all less than or equal to the average for the prior to device attachment time point plus one.

Alertness	Calmness/ agitation	Respirator response	Physical movement	Blood pressure (MAP)	Heart rate	Muscle tone	Facial expression	Points
Deeply asleep	Calm	No coughing and no spontaneous respiration	No movement	Below baseline	Below baseline	Totally relaxed; no tone	Totally relaxed	1
Lightly asleep	Slightly anxious	Spontaneous respiration with little or no response to ventilation	Occasional, slight movement	Consistently at baseline	Consistently at baseline	Reduced	Normal; no facial tension evident	2
Drowsy	Anxious	Occasional cough or resistance to ventilator	Frequent, slight movement	Infrequent elevations of 15% or more (1–3/observ.)	Infrequent elevations of 15% or more (1–3)	Normal	Tension evident in some facial muscles	3
Fully awake and alert	Very anxious	Actively breathes against respirator or coughs regularly	Vigorous movement limited to extremities	Frequent elevations of 15% or more (>3/observ.)	Frequent elevations of 15% or more (>3)	Increase tone and flexion of fingers and toes	Tension evidence throughout facial muscles	4
Hyper alert	Panicky	Fights ventilator, coughing or choking	Vigorous movement, including torso and head	Sustained elevation ≥15%	Sustained elevation ≥15%	Extreme muscle rigidity and flexion of fingers and toes	Facial muscles contorting and gromacing	5

MAP, mean arterial pressure. Data from Ambuel and coworkers [3].

Figure 39: The COMFORT Scale used for Monitoring Sedation Levels in Children.

9.7 Helmet Design Movement Test

The purpose of this test is to determine if the Flex Sensor will remain in place when placed in our helmet attachment method and subjected to simulated patient movement.

9.7.1 Equipment Used

- Helmet Attachment Method.
- Baby model: the baby model used here is simply a baby doll (Lakeshore Learning Item # DS802) covered in plastic wrap to cover up hair texturing and mimic baby skin smoothness).
- Flex Sensor on helmet design.
- Orbital shaker (borrowed from Dr. Ghosn).
- Tape.
- Ruler.
- Cardboard box.
- Permanent Marker.

9.7.2 Testing Instructions

1. Place Flex Sensor inside of helmet.
2. Mark spots on baby head as shown in **Figure 40**.
3. Place helmet on baby model.
4. Mark initial location of Flex Sensor on helmet by drawing spots on helmet design corresponding with the initial location of the helmet on top of the baby head with marker right over the spots marked in step 2.
5. Place baby model in cardboard box and place cardboard box on orbital shaker.

6. Secure cardboard box to orbital shaker with tape.
7. Set orbital shaker to shake at 150 RPM and wait 7 days. This simulates normal baby movement for a week.
8. Use tape and ruler to measure vertical and horizontal displacement of Flex Sensor.

9.7.3 Data Analysis and Statistical Techniques

The vertical (y) and horizontal (x) displacement of the helmet at the three marked points will be measured and an average taken. The average will then be compared with the found maximum displacement in x- and y- directions in the "Change in accuracy due to position" test.

9.7.4 Acceptance Criteria

The test will be successful if it moves less than the accepted x- and y- maximum displacement tolerance and the device will be considered viable for long term usage.

Figure 40: Locations to mark on baby head model for helmet movement testing. (Top View)

9.8 Adhesive Stickiness

The purpose of this test is to determine the length of time in which the adhesive used to attach our device to a patient will retain its adhesive properties.

9.8.1 Equipment Used

- 2 people.
- 4 Flex Sensors.
- 8 Adhesives (SKU-187900).

9.8.2 Testing Instructions

1. Remove adhesives from packaging and place Flex Sensors in between two adhesives.
2. Place adhesive on upper arm of participant. Repeat for both arms of each participant.
3. Monitor adhesives for period of one week.
4. Note time in which adhesive loses adhesive properties. If the device fails to lose adhesive properties within the monitored period, remove the device from the participant's arm and mark the time as >7 days.

9.8.3 Data Analysis and Statistical Techniques

The average time required for the adhesive to fail will be tested for whether or not it is statistically less than our expected goal (48 hours) using a t-test for independent samples assuming equal variances with α= 0.05.

9.8.4 Acceptance Criteria

Our device will pass the test if the adhesive remains on the participants for over 48 hours on average. Although our target maximum time for monitoring is 7 days, because we expect increased movement and sweating per day from our participants compared to conditions from patients in a neonatal ICU, we believe that after 48 hours, this test will capture conditions similar to 7 days in a neonatal ICU.

9.8.5 Testing Results

The DuoDERM Extrathin Wound Dressing remained on all test subjects for a period of 7 days. Because test subjects made no additional lifestyle changes for this test, the adhesive experienced patient movement equal to, if not greater than, the movement of an infant during a week in an intensive care unit. Because of this, we believe our device will be able to stay on an infant for a period of one week.

9.9 Zero Drift

This test will determine if our device will experience a loss of accuracy following long periods of continuous monitoring.

9.9.1 Equipment Used

- Device: for this test, attachment method 1 is used.
- Iterated Calibration Blocks.

9.9.2 Testing Instructions

1. Calibrate device as per instructions.
2. Use adhesive to secure device on a flat surface.
3. Wait for 7 days.
4. collect data stored on SD card.

9.9.3 Data Analysis and Statistical Techniques

An ANOVA statistical test with α = 0.05 will be used to confirm that the null hypothesis (the device accuracy is different over time) was failed to be rejected at each angle tested.

9.9.4 Acceptance Criteria

If ANOVA confirms that the null hypothesis was failed to be rejected at each angle, our test will have proved that accuracy of our device does not degrade significantly over time in the time tested. If it shows that only a few groups lose significant accuracy over time, the test will have failed for those angles of measurement and further testing may be required to narrow down the ICP range at which accuracy is significantly reduced. Else, the device will not pass the test.

10 Recommendations and Summary

Given the accuracy and non-invasive nature expressed in our testing results, Bend-Aid has tremendous potential to replace insufficient measurement techniques such as ventriculostomy and fontanelle palpation, in our target population. However, before it is implemented, our team suggests the following recommendations to ensure the quality and functionality of our device ranked in order of importance:

1. Conduct clinical testing to refine the mathematical model comparing fontanelle bulging angles with measured ICP through ventriculostomy.

   Our device uses a mathematical model derived from literature values as described in previous sections. We have tested our device against these literature values assuming they are correct. However, it is essential we refine our model to include as many data points as possible to ensure robust and accurate measurement of ICP. It is also essential to test whether our device does in fact measure ICP accurately by comparing Bend-Aid's output ICP values with the current standard of ventriculostomy. Our team suggests gathering this data in infants that already have the ventriculostomy procedure so as to not pose an unnecessary physical toll on trial subjects.

2. Develop a more reliable sensor that is able to detect bulging angle in at least two axes.

   Currently, our device utilizes a single-axis flexible sensor to determine the fontanelle bulging angle. Though this is sufficient if the device is placed perfectly on the fontanelle, a sensor that can detect flexing changes in two dimensions would be ideal. We envision a mesh containing several small sensors placed across the area of the adhesive (keeping the edges free of sensors to allow for sufficient area to hold the device in place while calibrating) that, if resolved computationally, can give a three-dimensional image of the fontanelle. The correct placement of the device on the fontanelle will thus not be as essential or difficult to achieve, as the sensor will be able to measure the angle of bending with the sensor mesh as long as the fontanelle is completely enclosed by it.

3. Create new software that can determine the apex of the fontanelle bulging to more accurately determine fontanelle bulging angle.

   If a two-dimensional sensor is implemented, a corresponding computational software will be needed to determine the angle of bending of the fontanelle.

4. Refine existing software to ensure it is efficient and accurate.

   Our software is functional and quick, but should be analyzed by people more familiar in computer science to make sure it is as efficient and accurate as possible.

5. Implement an alert system that is able to track changes over time.

   Our alert system currently operates using a threshold range to determine which LED needs to be lit up. However, ICP values naturally fluctuate in a range of ±10 cmH_20, and medical

professionals are looking for early detection of whether ICP is rising or not over instantaneous ICP measurements. To meet clinical needs, the device would be able to show if the ICP is a) within normal values and stable over time, b) at slightly increased values but stable over time, or c) at dangerous values OR within any value but increasing over time. The latter case is what medical professionals are looking for, and refining the alert system could provide this data more reliably.

6. Develop a standalone intuitive user interface compatible with either a portable computer or existing ICU monitors.

   Our device currently runs on Arduino and can be run without a computer. This is sufficient, but ideally our device could run on an monitor as well with a standalone user interface or be connected to existing ICU monitors to ease the device implementation into a professional medical environment.

7. Improving design of the device casing and removing cables.

   Although not essential for its functioning, Bend-Aid's designed could be improved to to reduce the risk of someone accidentally removing some of the hardware in the device, make its use more convenient and streamlined, and increase its visual appeal. Removal of cables, although not essential, would help make the device interfere less with other components like IVs. If cables are removed, however, it's important to test whether the Bend-Aid is able to filter out noise from other devices in the ICU.

8. Developing larger sizes for infants with hydrocephalus.

   Though rare, in extreme cases of hydrocephalus the fontanelle can expand beyond the working length of our current sensor (2.2 inches). According to our sponsors, having a quantitative ICP reading for these cases may help caretakers in developing countries accept that hydrocephalus is an abnormal condition and thus seek medical attention for their children.

A final recommendation has to do with commercialization of our device as we have had issues filing for Intellectual Property rights with Texas Children's Hospital. We recommend having a tech commercialization group, including a faculty neurosurgeon champion from Texas Children's Hospital to resolve this issue.

To achieve the suggestions above, our team suggests that the device be taken on by a continuing, interdisciplinary senior design team at Rice University with members in the Bioengineering, Computational Science, and Electrical Engineering departments. An alternate route would be to contact Dr. Black at TMCx to see if someone could complete these recommendations through the TMCx program and resources.

In conclusion, our team has constructed Bend-Aid: a novel, non-invasive device to measure intracranial pressure in infants under 18 months old utilizing the degree of bulging of the fontanelle to calculate an intracranial pressure reading. Bend-Aid is, to our knowledge, the only device currently being developed that focuses on the target population - infants - and that utilizes fontanelle

bulging angles to determine intracranial pressure continuously. Our device calibration allows the user to account for differences in sensor resistances and the unique curvature of each infant head. We have conducted several tests to prove Bend-Aid is accurate to clinical standards, non-invasive, continuous, quick to set up and intuitive, safe, and provides stable measurements over 7 days. Bend-Aid could be implemented in neonatal intensive care units to replace fontanelle palpation and, due to its low starting cost and restock cost, could even be implemented in low resource settings to bring quantitative ICP readings to an underserved population.

11 Appendix

11.1 List of Brainstormed Solutions (Brainstorm I)

1. **Patients Below 18 Months Old:**
   (a) *Qualitative Measurements*
      (i) Wait for babies to learn how to talk and ask them how they feel
   (b) *Slightly Invasive Procedures*
      (i) Attach oil drilling pump to skull and measure pressure
   (c) *Measuring Other Parameters Correlating them to ICP*
      (i) Put a light through brain hole, measure absorbance
   (d) *Image Processing - Physical Measurements*
      (i) Helmet/headband that measures head circumference
   (e) *Measuring/Analyzing Reactions*
      (i) Poke the soft spot of baby's head
      (ii) Artificially fuse babies skull
      (iii) Don't shake the baby and measure bulging
      (iv) Shake the baby and measure bulging
      (v) Palpate heads really well
      (vi) Caliper that correlates baby head to ICP - quantitative version of feeling baby head
   (f) *Exploiting Holes to the Brain*
      (i) Unicorn sensor (measuring through baby hole - babies aged below 18 months old have unfused skull "fontanelle")
2. **Patients Above 18 Months Old:**
   (a) *Qualitative Measurements*
      (i) Questionnaire
      (ii) Have patients write/draw something observe quality (double vision)
      (iii) Film a moving television commercial detailing high ICP that convinces patients to go to a doctor
   (b) *Measuring Other Parameters Correlating them to ICP*
      (i) Turn people around and see if they are more dizzy
   (c) *Image Processing - Physical Measurements*
      (i) Gait analysis (motion)
3. **Both Age Groups:**
   (a) *Signal Processing*

(i) Helmet that measures ICP through brain waves
(ii) Electrodes

(b) *Qualitative Measurements*

(i) Hire Shia LeBoeuf to motivate patients to regulate ICP
(ii) ICP monitoring mood ring

(c) *Slightly Invasive Procedures*

(i) Use multiple less invasive catheters to measure
(ii) Inject water soluble nanotubes into spinal space
(iii) Poke finger/artery for flow velocity associate w/ ICP
(iv) ICP acupuncture
(v) Shock patients and check recovery time - related to ICP
(vi) Induce high ICP in identical twin and measure ICP invasively in twin
(vii) Catheter that runs from spinal cord to brain

(d) *Weighing the Head*

(i) Weigh the head
(ii) Weigh the head of baby/adult using a pillow (how much pillow bends)

(e) *Measuring Other Parameters Correlating them to ICP*

(i) Jugular vein sensor
(ii) Tympanic membrane IR sensor
(iii) An app that uses the flashlight on my phone on my ear to measure pulse and pressure
(iv) Throat pulse oximeter
(v) Measure pulse through behind ear and relate to pressure
(vi) Laser diameter of major arterial
(vii) Measure temperature of brain
(viii) Face temperature (redness)
(ix) Grip strength with ICP
(x) Measure O2 consumption in brain
(xi) Blood pressure cuff but for head (pump air into cuff)
(xii) Do halo test variation
(xiii) IV systolic and diastolic
(xiv) Make a mathematical model but do it better
(xv) Radius of eye nerve + computer = quantitative optic nerve sheath diameter
(xvi) Find way to connect vital with ICP

(f) *Fluids*

(i) Bath tub see how the H_20 reacts to ICP
(ii) Throw patient into water and see if their head floats

(iii) Use IV fluid tube and find correlation with ICP
(iv) Inject fluid through ear and gauge resistance
(v) Push fluid down to throat and measure throat diameter
(vi) Measure cerebrovascular pressure reactivity - pump stuff into blood and see how CBF changes

(g) *Image Processing - Physical Measurements*
(i) Motion capture system (camera)
(ii) Bubble level (shows how level or flat surface is)

(h) *Measuring/Analyzing Reactions*
(i) Pinch skin of head and look at swelling
(ii) If people vomit, analyze the stuff they vomit
(iii) Concentrations of protein in blood
(iv) See if immune response occurs from swelling

(i) *Sounds and Frequencies*
(i) Knock on the brain and tell the ICP from the sound (similar to how you knock on watermelons)
(ii) Shake or vibrate the patient (fluid vibrates a lot)
(iii) See if patients with high ICP can hear different frequencies of sound
(iv) Resonant frequency (echolocation)
(v) Voice recognition (tell ICP from voice frequency)
(vi) Use tuning fork on the brain

(j) *Eye-Related*
(i) Look at pupil of eye with camera or sensor
(ii) Contacts that incorporate a sensor
(iii) Eye patch for optic nerve sheath diameter (ONSD) measurement
(iv) Make a Snapchat filter that measures ICP based on eye parameters
(v) Glasses with sensor to look at optic nerve sheath
(vi) Sensor that goes through eye to brain

(k) *Magnets and Capacitors*
(i) ICP with magnetic field
(ii) Magnetic coupling pressure sensor
(iii) Measure pressure by treating the brain as a capacitor

(l) *Exploiting Holes to the Brain*
(i) Ear pressure measurer that relates to ICP in the brain
(ii) Blow your nose really loud and the pressure will relate to ICP
(iii) A liquid column that enters the nose and measures pressure
(iv) Bubbles in tube

(v) Sensor on the back of neck (through neck hole)

(vi) Throat pressure gauge (through neck hole where brain stem goes)

(vii) A tube that looks at your brain through your nose

11.2 List of Brainstormed Solutions (Brainstorm II)

1. **Attachment Method:**

   (a) Trident (**Figure 5**)

   (b) Headband

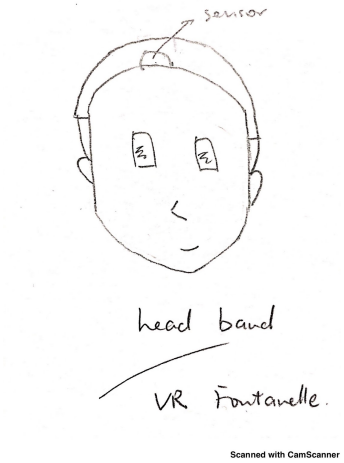

Figure 41: Head Band / VR Fontanelle. This method takes the same shape of what head bands and VR goggles would look like, and a sensor would be attached to the inside of the device to capture the signal from the fontanelle.

   (c) Brain Web

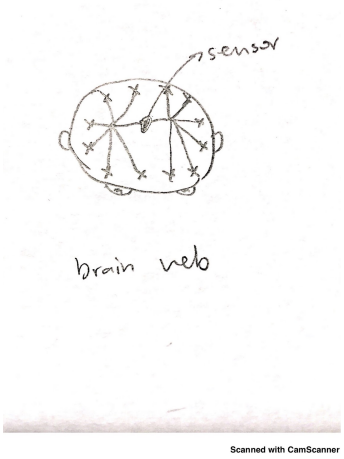

Figure 42: Brain Web. Inspired from the attachment of electrodes, the many attachment points allow for a smooth and close to scalp contact for the sensor.

   (d) Plastic Casing with LEDs to Ensure Proper Placement (**Figure 7**)

   (e) SurePulse Heart Rate Monitoring Cap (**Figure 6**)

2. **Measurement Method:**
   (a) Use Flex sensor (Pressure Sensor) to Measure Angle of Fontanelle Bulge (**Figure 8**)
   (b) Non-Contact, Air Puff Tonometer (**Figure 9**)
   (c) Contact Tono-Pen-Inspired (Used for Eye Pressure) Pressure Sensor [52]
      (i) Miniaturized tonometer
      (ii) Uses plunger that comes in direct contact with the cornea
      (iii) Measures the reaction force using a strain gauge
   (d) Poke
      (i) How 3D printer gently touches the printing bed before starting a print
      (ii) Motor push down a little bit and measure immediate bulging back / resistive force felt
   (e) Diaphragm pressure gauges (**Figure 10**)
   (f) Fontanelle Displacement due to Pulsatile Pressure[53]
      (i) Elasticity of fontanelle changes with ICP
      (ii) Displacement of fontanelle caused by ICP and pulsatile pressures - Pulsatile pressures proportional to mean arterial pressure, which we can most likely easily measure
      (iii) Mean arterial pressure divided by displacement due to pulsatile pressures = fontanelle elasticity, which can be correlated to ICP
   (g) Noninvasive laser blood pressure measurement [54]
      (i) Previous research shows success in measuring rabbit ICP using laser methods
   (h) Infrared Pressure Sensor/Displacement Sensor [55]
      (i) Near Infrared Spectroscopy
   (i) Arterial blood pressure (ABP) and Cerebral blood flow velocity (CBFV) [56]
      (i) May require a finger cuff vital sensor and transcranial doppler probe

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