A Study of Measuring Intracranial Pressure Using a Non-Invasive Piezoelectric Sensor

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ABSTRACT

The brain, like many parts of the human body, can experience swelling, also known as cerebral edema. Cerebral edema may occur because of an injury, health related issues, tumors, or even high altitudes[1]. When cerebral edema occurs, a rise in intracranial pressure (ICP) becomes prevalent and may cause a serious threat.

Without immediate treatment, increased intracranial pressure can prevent blood from flowing to the brain and depriving it of necessary oxygen it needs to function. A normal ICP is usually between 5-15 mmHg (666 Pa - 1333Pa). Any ICP observed to be above 20 mmHg (2666Pa) can be associated with brain ischemia and is usually treated[2, 3]. If prolonged, high intracranial pressures can be fatal.

Current methods of measuring increased ICP are invasive and may involve drilling into the skull. Extreme invasive measures are not always suitable for certain situations. This thesis presents a study of a non-invasive sensor using piezoelectric PVDF wire to measure the ICP. The PVDF wire sensor is wrapped around the outer portion of the human head to measure the integrated hoop strain. Using this hoop strain, the pressure is then calculated from a known coupling factor of strain to pressure outputted from finite element modeling simulations. The coupling factor is then incorporated into a final calibration factor to calibrate the piezoelectric PVDF wire sensor from charge (Picocoulomb) to pressure (Pascal). These calibration factors are proven to be primarily dependent on the circumference of the human skull.

Furthermore, part of this study analyzed the effectiveness and validity of the sensor due to asymmetries in the human skull. A comparison of analytical analysis results versus computational results using finite element modeling simulations show that the PVDF wire sensor neglects any asymmetries presented within the test subject. The results of this study show that this sensor will output correct ICP measurements of different subjects using appropriate calibration factors and is a viable option for measuring ICP non-invasively.
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Chapter 1. Introduction

1.1 Problem Statement

Swelling, the body’s reaction to an injury, occurs quickly and is rather simple to treat. Effective methods include rest, ice, medication, elevation, or the removal of the fluid. But what happens if the brain swells? The brain is also prone to swelling from an injury and other causes such as high altitudes, tumors, and other health related issues. Cerebral edema poses several threats to the human body, one of which is increased intracranial pressure (ICP). Prolonged ICP can result from minor symptoms such as headaches, dizziness and vomiting to more severe symptoms such as memory loss, vision loss, and seizures [1]. An increase in intracranial pressure can even cause fatality. Treatment of increased ICP is extremely invasive and should only be performed if there is a certainty that an increased ICP exists. With this in mind, the ability to measure the ICP through non-invasive means is of utmost importance. This is critical especially in remote, harsh environments where one needs to be certain that a threat of increased ICP exists in order to take preventive precautions. Such an environment includes space, where astronauts are more prone to increased ICP due to microgravity[4].

1.2 Current Methods of Measuring ICP

1.2.1 Lumbar Puncture (Spinal Tap)

The most common means of measuring ICP from the cerebral spinal fluid (CSF) is from a lumbar puncture, also known as a spinal tap. In this method, the patient must lie on his or her side in a fetal position or may be sitting but bent over. A local numbing anesthetic is then injected into the lower back. Lastly, a spinal needle is inserted into the same location to measure the CSF pressure. Occasionally, special x-rays are used to help guide the needle into the correct location known as fluoroscopy. This method is overall less invasive than other techniques but still requires penetration into the human body with a needle and also may require x-rays. Furthermore, this technique may not be used if the patient has former back problems or infections[5]. Figure 1 displays the procedure of measuring ICP from lumbar puncture[6].
1.2.2 External Ventricular Drainage (EVD)

If the former technique is unavailable, the patient must get measurements of ICP through other means, which usually requires hospitalization. Currently the most effective and considered the “Gold Standard” of measuring ICP is through external ventricular drainage (EVD). Monitoring ICP through the EVD technique involves inserting a catheter into one of the lateral ventricles through a frontal burr hole[7, 8]. This area of the head contains the fluid between the brain and skull known as cerebral spinal fluid (CSF). This fluid-filled catheter can then be connected to a standard pressure transducer. Another option is using a catheter that has a built in pressure transducer. Catheters with built in pressure transducers have better quality ICP measurements compared to catheters attached externally to a separate pressure transducer. Not only does the use of a catheters measure the global ICP, but it can also be used to drain the cerebral spinal fluid. Although EVD may have its advantages, it does have some disadvantages that cannot be overlooked. EVD is extremely effective and accurate, but highly invasive. EVD has also been associated with posttraumatic hemorrhages and infections[7].

1.2.3 Subdural Screws and Epidural Sensor

Two other procedures that involve monitoring the ICP through the skull are subdural screws and an epidural sensor. Both require drilling a burr hole through the skull. The difference between the methods is where the burr hole is located on the skull. Subdural

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**Figure 1.** Location for lumbar puncture technique. Lumbar Puncture, 2003, "Miller-Keane Encyclopedia and Dictionary of Medicine, Nursing, and Allied Health.," [http://medical-dictionary.thefreedictionary.com/Lumber+puncture](http://medical-dictionary.thefreedictionary.com/Lumber+puncture). Used under fair use, 2014.
screws are used if there is an immediate need to monitor the ICP. With subdural screws, a hollow screw is inserted through the skull and into the membrane that protects the brain and spinal cord, known as Dura mater. For an epidural sensor, it is also inserted through a hole in the skull but between the skull and Dural tissue. It is said to be less invasive than other techniques[5]. Figure 2 displays where the lateral ventricles, epidural, and subdural procedures take place[9-11].

![Figure 2](image)


1.3 Related Research of Non-Invasive Measuring of ICP

1.3.1 Transcranial Doppler (TCD)

Currently the non-invasive techniques are not nearly as accurate as the invasive techniques used to measure ICP. Furthermore, the non-invasive techniques are complex and cannot be used on a larger percentage of patients due to different anatomical differences[7]. One of the techniques that are non-invasive is transcranial doppler (TCD) ultrasound. This technique is a non-invasive ultrasound that measures the cerebral blood flow velocity[12].

From TCD, echoes generate an electrical impulse with the ultrasound probe and can be used to produce the peak systolic velocity (PSV) and end diastolic velocity (EDV). Using these values and the mean flow velocity, the pulsatility index is derived in equation (1),
The pulsatility index is found to have a correlation with ICP[13]. However, since the main premise of TCD is ultrasound, the probe must be measured where the skull or bone is thinnest. Occasionally, TCD cannot be used due to the ultrasound not being able to penetrate the skull. Also, the technique of TCD is extremely operator dependent and requires specific training and repetitive exercises[7]. As of now, TCD still requires further validation for use of measuring TCP. Figure 3 provides an image of TCD[14].

Figure 3. Transcranial doppler technique. Mayfield Clinic, 2013, "Subarachnoid hemmorhage," http://www.mayfieldclinic.com/PE-SAH.HTM-.U0boOsdwRUmE. Used under fair use, 2014.

1.3.2 Tympanic Membrane Displacement (TMD)

Another non-invasive technique is tympanic membrane displacement (TMD). Tympanic membrane displacement comes from an acoustic reflex that stimulates the stapedius. The stapes rests on an oval window, which is covered by a membrane. Because this membrane is flexible, the pressure of the fluid inside the cochlea affects the movement of the membrane and the stapes. This movement has been shown to correlate with ICP[7, 15, 16]. Like many non-invasive techniques, TMD also has its flaws. In a study done by Shimbles et al. [17], the technique proves to have a low success rate for taking the measurements. Two thirds of the subjects tested in the study group were exempted from analysis due to a combination of failed tympanometry and a lack of demonstrable cochlear aqueduct patency. Furthermore, the study shows that age could be a factor in successful TMD measurements. A significant difference appears from subjects under the age of 40 compared to subjects above the age of 40[17]. Because of the lack of failed measurements, without even concerning accuracy, TMD is not a reliable non-invasive technique for measuring ICP.
1.3.3 Optic Nerve Sheath Diameter (ONSD)

Another non-invasive technique is known as optic nerve sheath diameter (ONSD). The technique uses the fact that the dural sheath surrounds the optic nerve. In between this sheath and the white matter exists the subarachnoid space, which also communicates with the subarachnoid space surrounding the skull[7]. The subarachnoid space can be seen in Figure 2. When an increased ICP occurs, the dural sheath expands which can be seen using transocular ultrasound. A study by Kimberly[18] observed the direct relationship between the nerve sheath diameter and invasively measured ICP through EVD. A correlation of ICP from ONSD and using EVD as a reference standard was confirmed by Kimberly[18]. Although a correlation exists, ONSD has its flaws as well. Because the technique uses ultrasonography, it requires training and has operant measurement variance. Furthermore, the use of ONSD depends on the health status of the patient. Optic nerve sheath diameter could be enlarged because of secondary involvement such as tumors, inflammation, Graves’ disease, sarcoidosis [7, 19, 20].

1.4 Research Concept

The purpose of the study is to create and validate a non-invasive ICP sensor that addresses the issues of current non-invasive ICP measuring techniques. The most notable issue with the other non-invasive techniques is the anatomical differences from one patient to another affecting how the sensor performs. For example, if the patient has current health problems that have already increased the optic nerve sheath, then ONSD technique will not be applicable. Another example is with transcranial Doppler technique. Because TCD requires the use of ultrasound, thicker skulls could prevent penetration of the ultrasound. Other problems are that recent non-invasive ICP measuring techniques require precision and expert training. The resulted measurements are highly dependent on the operator and could vary if not used properly. With these problems in mind, using a piezoelectric PVDF wire sensor will enable some of the problems to become negligible. To install the sensor, the piezoelectric PVDF wire is wrapped a number of complete turns around the outer head diameter of the patient. Because of the nature of piezoelectric PVDF wires, this will measure the integrated hoop strain around the skull. The hoop strain measures the strain integrated over the circumference length of the skull. This strain is caused by the intracranial pressure pushing against the interior walls of the skull and causing the skull to expand. Figure 4 displays a concept model of the interior pressure causing the skull to expand outward. Refer to Appendix A for further fundamental hoop strain theory.
Ultimately, this hoop strain will factor out all the asymmetries of the skull and allow the sensor to be used on multiple patients with different shaped skulls. The theory behind piezoelectric PVDF wires will be discussed in further detail within Chapter 2: Background.

1.5 Research Objective

The overall objective of this study is to analyze and design a non-invasive ICP sensor using a piezoelectric PVDF wire through analytical and finite element analysis. Listed below are the research goals:

- Calculate the hoop strain of a simple 2D circular model with various sizes and various asymmetries through analytical analysis and finite element analysis (COMSOL)
- Calculate the hoop strain of a simple 2D realistic model with various sizes and various asymmetries through analytical analysis and finite element analysis (COMSOL)
- Calculate the hoop strain of a simple 3D circular model with various sizes and various asymmetries through analytical analysis and finite element analysis (COMSOL)
- Calculate the hoop strain of a simple 3D realistic model with various sizes and various asymmetries through analytical analysis and finite element analysis (COMSOL)
- Compare results from analytical analysis and computational analysis of all 2D and 3D simple model results – Confirm that asymmetries are neglected and have no affect on hoop strain.
- Design and create a test rig to simulate a test article being pumped with fluid and measure the experimental hoop strain with PDVF wire.

Figure 4. Concept of internal pressure causing human skull to expand.
• Develop a finite element model of the experimental test article and obtain the coupling factor of strain/pressure outputted from COMSOL. This coupling factor will be used as the final variable in the calibration factor to calibrate the PVDF wire sensor from Coulombs to Pascals. Figure 5 displays a block diagram explanation of how the calibration factor is solved.

![Calibration Factor Diagram](image)

**Figure 5.** Block diagram of how calibration factor is solved.

• Apply calibration factor to experimental piezoelectric PVDF wire sensor data.
• Validate measured hydrophone pressures to measured piezoelectric PVDF wire sensor pressure.
• Verify that asymmetries are negligible when using piezoelectric PVDF wire sensor and determine attributes which affects the calibration factor.
• Calculate calibration factors for different size craniums.

1.6 Thesis Structure

This thesis is structured similarly to how the research goals are stated. Chapter 2 goes into detail on background information needed to understand how piezoelectric PVDF wires work. Chapter 2 also discusses the foundation of Fourier analysis and the equations associated with solving hoop strain. Lastly, background information is given on the theory of finite element modeling within COMSOL.

Chapter 3 covers the preliminary testing done to show that asymmetries should have no affect when measuring hoop strain. Chapter 3 discusses the analytical and computational analysis done for preliminary testing. Chapter 4 describes the design of the experimental test rig and the procedures used to acquire data as well as the experimental results. Chapter 5 uses the same test articles in Chapter 4 to model the test rig in finite element modeling. Chapter 5 sets out to find the calibration factor of the piezoelectric PVDF wire sensor and also determines what factors are associated with the calibration factor. Chapter 6 covers the comparison of the experimental analysis to the finite element analysis and discusses the calibration factors acquired. Lastly, Chapter 7 sums up the thesis covering all results and conclusions and future recommendations.
Chapter 2. Background Information

2.1 Piezoelectric PVDF Wire Sensor

One of the key components of piezoelectric materials is how they behave. Piezoelectric materials possess a unique characteristic unlike any other materials called the piezoelectric effect. The direct piezoelectric effect is a creation of electric charge due to an applied stress. The converse piezoelectric effect is an applied electric field or charge, which in turn produces a proportional strain, expansion, or contraction[21]. An example of a piezoelectric material is piezoceramics, also known as piezoceramics. The first step into creating piezoceramics is mixing together proportional amounts of metal oxide powders and heating the mixture to create a uniform powder. This powder is then mixed in a binder and formed into the desired shape. As a result of this process, the powdered particles sinter and form a dense crystalline structure as seen in the left of Figure 6[22, 23].

![Figure 6. Crystalline structure before and after polarization.](image)

As the material cools down, each crystalline structure has a tetragonal symmetry and an associated dipole moment. Adjoining dipoles form regions of local alignment known as “domains”. This alignment gives a net dipole moment to the domains, and thus a net polarization. However, as seen in Figure 7 (a), the direction of polarization among neighboring domains is random which causes no overall polarization to the ceramic.
Figure 7. Poling process: (a) Before polarization where domains are oriented randomly. (b) A large electric field is used for polarization. (c) Electric field is removed, remnants of polarization remain.

In order to align the domains seen in Figure 7 (b), a strong electric field is exposed to the ceramic. This process is known as “the poling process”. After this process, the domains closely aligned with the electric field expand at the expense of the domains not aligned with the electric field, thus causing the ceramic to expand. This is seen in the right of Figure 6. Once the electric field is removed, the dipoles remain mostly aligned, Figure 7 (c), and the crystal now has a permanent polarization and elongation[23].

Typically, piezocermics are used as actuators and polymer piezoelectric films are used for sensors[22]. In the case of this study, a piezoelectric (polyvinylidene fluoride) PVDF cable is used to sense the strains of the skull. Since the sensor is made using a piezoelectric PVDF film, the theory behind polymer PVDF piezoelectric films and PVDF piezoelectric cables are similar and relative to piezocermics. To begin, PVDF film normally has a random orientated crystalline structure. In order to convert the PVDF structure into a semi-crystalline beta structure, the film must be stretch in a 4:1 ratio in the machine direction to produce a mono-oriented film, or can be stretched in both the machine direction and transverse direction to create a bi-oriented film[24]. The advantages of creating a bi-oriented film include a more uniform thickness, better isotropic properties, no wrinkling when heated, and better long-term stability. The next process is the poling process as seen with the piezocermics.

The most widely used form of poling PVDF film is the “corona poling” process. The process involves placing the PVDF film on top of a heating plate with the bottom surface connected to a grounded electrode[25]. A corona tip is suspended above the PVDF surface and subjected to a high voltage. The air at the tip gets ionized with the tip’s polarity. Once the corona discharges, the ionize particles accelerate towards the ground on the bottom side of the PVDF film which causes a deposition on top of the PVDF surface. The charges remaining on the PVDF surface generate a poling electric field between the ground underneath the PVDF and the PVDF surface. The corona poling schematic can be seen in Figure 8[25].
The magnitude of the electric field can vary depending on the deposition of charges on the surface. This can be controlled by changing the distance of the metal grid placed between the corona tip and the PVDF film. The advantage of using the corona poling process is that it remains more forgiving towards PVDF film imperfections. Also, for commercial applications, large areas of PVDF film can be poled at one time[25]. Once this process is complete, the PVDF film will have domains that are aligned and the film will have a permanent polarization.

Once the PVDF film is polarized, the film possess the direct piezoelectric effect. The fundamental mechanical equations surrounding this behavior start with Hooke’s Law Equation (2), which relates the mechanical stress, $\sigma$, to the mechanical strain, $\epsilon$, by the compliance matrix, $s$,

$$\epsilon = s\sigma$$ (2)

The fundamental electrical equation (3) describes the electrical displacement, $D$, expressed as a function of electric field, $E$, related by the dielectric permittivity matrix, $e$.

$$D = eE$$ (3)

Piezoelectric materials couple both the mechanical and electrical properties to form the constitutive equations (4) and equation (5) [22, 26],

$$D_i = e_{ij}^E E_j + d_{im}^d \sigma_m$$ (4)

$$\epsilon_m = s_{mk}^E \sigma_k + d_{ml}^e E_l$$ (5)

The constitutive equations can also be written in matrix form,

$$\begin{bmatrix} D \\ \epsilon \end{bmatrix} = \begin{bmatrix} e^E & d^d \\ d^e & s^E \end{bmatrix} \begin{bmatrix} E \\ \sigma \end{bmatrix}$$ (6)
Notation $D_l$ is the electrical displacement and consists of a (3x1) vector with unit’s ($\text{Coulomb/m}^2$), Equation (7). Notation $\epsilon_k$ is the strain vector and consists of a (6x1) vector with dimensionless units, Equation (8). Notation $E$ is the applied electric field and consists of a (3x1) vector with units ($\text{Volts/m}$), Equation (9). Notation $\sigma_m$ is the stress vector and consists of a (6x1) vector with units ($\text{N/m}^2$), Equation (10).

\[
D_l = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix}
\]  
\[
\epsilon_m = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix}
\]  
\[
E_j = \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}
\]  
\[
\sigma_m = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix}
\]

The subscripts $k, m = 1, 2, \ldots, 6$ and $i, j = 1, 2, 3$ represents the axis direction as seen in Figure 9, which describes the axis nomenclature[23].

\[
\begin{array}{c|c}
\# & \text{Axis} \\
\hline
1 & x \\
2 & y \\
3 & z \\
4 & \text{Shear around } x \\
5 & \text{Shear around } y \\
6 & \text{Shear around } z \\
\end{array}
\]

**Figure 9.** Axis Nomenclature

The other piezoelectric constants within equations (2-4) are the dielectric permittivity matrix, $\epsilon_{ij}^\sigma$, with units ($\text{Farad/m}$).
\[ \epsilon_{ij} = \begin{bmatrix} \epsilon_{11}^\sigma & 0 & 0 \\ 0 & \epsilon_{22}^\sigma & 0 \\ 0 & 0 & \epsilon_{33}^\sigma \end{bmatrix} \]  

(11)

The superscript, \( \sigma \), is a representation that the permittivity matrix in equation (11) is measured at constant stress. The elastic compliance coefficient, \( s_{mk}^E \), has units \( (m^2/N) \).

\[ s^E = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \]  

(12)

The superscript, \( E \), is a representation that the compliance matrix in equation (12) is measured at constant electric field. The piezoelectric coefficients \( d_{im}^d \) and \( d_{m1}^c \), a \((3\times6)\) and \((6\times3)\) matrix respectively, have units \((Coulomb/N)\) or \((m/Volt)\). The piezoelectric electric strain constant, \( d_{im}^d \), defines electric displacement per unit stress at a constant electric field where as, \( d_{m1}^c \), defines strain per unit field at constant stress. In practice, these coefficients are numerically equal. The different superscripts, \( c \) and \( d \), from \( d_{im}^d \) and \( d_{jk}^c \) are used to differentiate the converse and direct piezoelectric effect. Since piezoelectric sensor applications are based on the direct piezoelectric effect, \( d_{im}^d \) is used,

\[ d_{im}^d = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \]  

(13)

The subscripts \( i \) and \( m \) in equation (13) represents the ratio of strain in the \( m \)-axis to the electric field along the \( i \)-axis when all stresses are held constant [23]. For example, \( d_{31} \), \( d_{32} \), and \( d_{33} \) represent strains in the 1,2, and 3 directions but all are relative to the electric field in the \( E_3 \) direction [22, 23]. The sensing constitutive equation (4) can be written in matrix form as,

\[ \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} \epsilon_{11}^\sigma & 0 & 0 \\ 0 & \epsilon_{22}^\sigma & 0 \\ 0 & 0 & \epsilon_{33}^\sigma \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \end{bmatrix} \]  

(14)

Since the piezoelectric PVDF film is used as a sensor where the applied external electric field will be zero, equation (14) is reduced to equation (15).
Equation (15) refers to the direct piezoelectric effect, which is when a stress field causes an electric displacement to occur. The electric displacement is then related to general charge from equation (16).

\[
\begin{bmatrix}
D_1 \\
D_2 \\
D_3
\end{bmatrix} = 
\begin{bmatrix}
0 & 0 & 0 & 0 & d_{15} & 0 \\
0 & 0 & 0 & d_{24} & 0 & 0 \\
d_{31} & d_{32} & d_{33} & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6
\end{bmatrix}
\] (15)

\[
q = \int \int [D_1 \ D_2 \ D_3] \begin{bmatrix} dA_1 \\ dA_2 \\ dA_3 \end{bmatrix}
\] (16)

The \(dA_1, dA_2,\) and \(dA_3\) are the components of the electrode area in the 2-3,1-3, and 1-2 planes respectively. Also note that the charge collected only depends on the infinitesimal area \(dA\) of the electrode normal to the actual electric displacement \(D\). The charge and voltage can then be related to each other by the sensors capacitance, \(C_p\), which is usually given by manufacturers.

\[
V = \frac{q}{C_p}
\] (17)

Therefore, by measuring the output voltage of the piezoelectric PVDF wire sensor, the charge is calculated and then converted to stress using equations (17), (16), and (15). From stress, the strain is calculated from knowing compliance properties of the selected piezoelectric material.

The theory and process of polarizing PVDF films into a usable piezoelectric sensor remains the same for piezoelectric PVDF cables. The only difference is that the PVDF cable is molded into a wire by extrusion processes before it is polarized. The polarization step is exactly the same and can be done with the “corona poling” method discussed earlier. Figure 10 displays the layers of a piezoelectric PVDF cable created by Measurement Specialties. The outer most layer of the cable is a polyethylene jacket, then a copper braided layer, then the piezoelectric polymer, and finally a copper core.

The theory of piezoelectric materials is used for modeling the piezoelectric PVDF wire sensor within a finite element model simulation.
2.2 Fourier Analysis

Fourier analysis is the study of representing general functions by use of simple trigonometric functions. The history of the Fourier series began when D’Alembert, Euler, and Bernoulli were trying to find the solution to a differential equation for a simple string with vibrations. Bernoulli gave a solution in the form of a trigonometrical series,

$$y = A_1 \sin x \cos at + A_2 \sin 2x \cos 2at + \cdots,$$

(18)

The importance of Bernoulli’s discovery was immediately recognized, and Euler pointed out that if this statement of the solution were correct, an arbitrary function of a single variable must be developable in an infinite series of sines of multiples of that variable[28]. Euler held this to be impossible, since a series of sine functions are both periodic and odd, and argued that if the arbitrary function didn’t have both of these properties, then it could not be expanded in such a series. At this time, Lagrange stated that when the initial displacement of the string of unit length is given by $f(x)$, and the initial velocity by $F(x)$, the displacement at time $t$ is given by

$$y = 2 \int_0^1 \sum (\sin n\pi x' \sin n\pi x \cos n\pi at)f(x')dx'$$

$$+ \frac{2}{a\pi} \int_0^1 \sum \frac{1}{n} (\sin n\pi x' \sin n\pi x \sin n\pi at)F(x')dx'$$

(19)

Because of this result and discussion of the problem which Lagrange gave in his memoirs, mathematicians have had doubts of the importance of Fourier’s discoveries and to have given credit to Lagrange for the proof of his development of an arbitrary function in trigonometrical series[28]. Furthermore, Euler and D’Alembert published discussions
in which the idea of the definite integral expressions for the coefficients in Fourier’s Series may be traced. Euler employed the method of multiplying both sides of the equation (20) by cos nx and integrating the series term by term between the limits of 0 and π to get equation (21)[28].

\[ f(x) = a_0 + 2a_1 \cos x + 2a_2 \cos 2x + \cdots + 2a_n \cos nx + \cdots \]  
\[ a_n = \frac{1}{\pi} \int_0^\pi f(x) \cos nx \, dx \]  

Although Fourier made no claim to the discovery of the values of the coefficients[28, 29], he stated that when the values in equations (22),(23), and (24) are plugged into equation (25), that the sum of the terms up to cos nx and sin nx is equal to equation (26).

\[ a_0 = \frac{1}{2\pi} \int_{-\pi}^\pi f(x')dx' \]  
\[ a_n = \frac{1}{\pi} \int_{-\pi}^\pi f(x') \cos nx' \, dx' \{n \geq 1\} \]  
\[ b_n = \frac{1}{\pi} \int_{-\pi}^\pi f(x') \sin nx' \, dx' \{n \geq 1\} \]  

\[ a_0 + (a_1 \cos x + b_1 \sin x) + (a_2 \cos 2x + b_2 \sin 2x) + \cdots \]  
\[ \frac{1}{\pi} \int_{-\pi}^\pi f(x') \frac{\sin \frac{1}{2}(2n + 1)(x' - x)}{\sin \frac{1}{2}(x' - x)} \, dx' \]  

He then discussed the limiting value of this sum as n approaches infinity and thus obtained the sum of the series now known as Fourier’s Series[28]. The importance of Fourier’s Series, which made Joseph Fourier stand out from the rest, was his interpretation of these integrals. Fourier made the bold claim that all arbitrary functions can be modeled by trigonometric series.

Fourier’s Series plays an important role in the analytical analysis section under the preliminary studies. Fourier’s Series will help demonstrate the idea that the piezoelectric PVDF cable wrapped a number of complete turns around the cranium only measures the hoop strain and inevitably cancels out all the asymmetries.
2.3 Finite Element Analysis

Finite element analysis (FEA), also known as the finite element method, is the process of solving for numerical solutions of field problems. A field problem requires known spatial distribution for one or more dependent variables. Mathematically, a field problem is described by differential equations or by an integral expression[30]. Either description may be used to formulate finite elements, which can be done using FEA programs such as COMSOL. The basic idea of FEA is to find the solution of a complex field problem by replacing it with a simpler one[31].

Finite elements can be visualized as small pieces of a structure. In each finite element, a field quantity is allowed to have only a simple spatial variation. Since the actual problem is much more complicated, FEA will only be able to find an approximate solution. Each element is connected by nodes, and multiple elements are used to form a structure. This structure of elements is also known as a mesh. Numerically, a finite element mesh is represented by a system of algebraic equations to solve for unknowns at each node. Nodal unknowns are the values of the field quantity, and when combined with the assumed field in any given element, will completely determine the spatial variation of the field in that element. Therefore, the field quantity over the entire structure is solved for element by element[30]. Although the FEA solution is an approximation, it is possible to improve or refine the solution by spending more computational effort, such as increasing the number of elements in a structure[30, 31].

The three main steps of solving a problem through FEA are classification, modeling, and discretization. The first step to solving any problem is to identify the problem. A few questions to help classify a problem are as follows:

- What important physical phenomena may exist?
- Is the problem dependent or independent of time? (static or dynamic)
- Is the problem linear or nonlinear?
- Does an iterative process need to be taken in order to solve?
- What results and to what accuracy is sought after from analysis?

A certain problem may not always lie in one category. Sometimes it is necessary to couple multiple physics or fields of study. Two types of coupling exist for modeling finite elements. Direct coupling implies that the individual physics influence each other while indirect coupling implies that only one physics influences the other[30].

The next step involves modeling. After an understanding of the physical problem, the user must include only the essential details of the model. In this case, the model is not overly complicated but will still allow the problem to be solved with sufficient accuracy. A geometric model becomes a mathematical model when the behavior is approximated by selected differential equations and boundary conditions[30].Finite element analysis is a simulation, not a reality. Therefore, the mathematical model is an idealization, in which the geometry, loads, boundary conditions, material properties, and so on are simplified based on the analyst's understanding of the problem.
The last step is discretization, which is when the mathematical model is divided into a mesh of finite elements. Thus a fully continuous field is represented by a piecewise continuous field defined by a number of nodal quantities and simple interpolation within each element[30]. Discretization, like modeling, is also an approximation. Therefore, in finite element analysis, there are two approximations. Modeling approximation error can be reduced by improving the model such as boundary conditions, loads, and so forth. Discretization error can be reduced by increasing the number of elements and refining the mesh. Lastly, computational error or numerical error exists when a finite precision is used to represent the data[30].

The finite element analysis in this study is performed using COMSOL. COMSOL is a multiphysics finite element modeling program. The steps to create a finite element model begin with choosing which physics module to use. Within COMSOL, there are many modules or physics that the user can choose from depending on what applications are needed. For this study, the main focus will be on structural mechanics[32]. The structural mechanics module can model static and dynamic analyses in 2D, 2D axisymmetric, and 3D coordinate systems for solids, shells, plates, trusses, and beams. Within the structural mechanics module are physics interfaces. These interfaces are the backbone of the module and have predefined formulations to help solve for the finite element solutions. The following physics interfaces that will be used in this study are[32]:

- **Solid Mechanics** – This physics defines the quantities and features for stress analysis and general linear and nonlinear solid mechanics, solving for the displacements. The default material is a linear elastic material. Other options include viscoelastic and hyperelastic materials. The elastic materials can be extended with plasticity, thermal expansion, damping, and initial stress and strain components. These elastic materials can also be isotropic, orthotropic, and fully anisotropic.

- **Piezoelectric Devices** – This interface combines the solid mechanics and electrostatics interfaces to model piezoelectric materials. The piezoelectric coupling will be in a strain-charge form.

After a physics module is selected, a geometry must be created. This can either be done within COMSOL by using arbitrary shapes or lines or by importing a solid geometry from an external program. Most frequently used are computer-aided design programs such as SolidWorks. The analysis must use classification techniques to decide how the geometry is to be built. Questions such as whether a 2D model is sufficient enough to gain accurate information or if an axisymmetric model exists can greatly reduce the computational cost of finding a solution.

The next few steps include defining what the material properties are to be used. COMSOL has common materials built into the program. However, if a specific material is not included, analysts have the ability to manually input material properties. The next stage calls for applying loads and boundary conditions. This step is crucial in order to mimic reality to insure a realistic result. Boundary and load conditions can be set on domains, faces, or points depending on whether a 2D or 3D model is being used. A
mesh, which describes the entire element assembly, determines where the calculations of the differential equations take place. COMSOL has an automated mesh function which will create a mesh depending on what boundary conditions and multiphysics are being used. An analyst can also edit the built in mesh or create their own mesh from scratch. Meshes are usually built from triangular or quadrilateral elements.

Once the physics, geometry, boundary conditions, and mesh are chosen, a study must be selected. COMSOL includes a number of preset study types such as eigenfrequency, frequency domain, stationary, and time dependent. For the purpose of this study, the focus will be on frequency domain. Once the study runs, post processing can be done on the data calculated. From here, the analyst is able to study the stresses or strains within the structure, examine how the structure deforms or deflects, determine what potential voltage the piezoelectric device outputs, and much more. Regarding the exact COMSOL model used and equations involved will be discussed in detail within Chapter 3 Preliminary Studies and Chapter 5 Finite Element Modeling.
Chapter 3. Preliminary Studies

3.1 Preliminary Finite Element Analysis

3.1.1 Introduction of 2D Preliminary Finite Element Analysis

The main purpose of this preliminary study is to understand the concept of measuring hoop strain and to verify that measuring hoop strain integrates out all asymmetries. The reason that the concept of integrating out all asymmetries is important to this study is because in order for the piezoelectric PVDF wire sensor to work properly as a universal sensor, variations of the skull must not affect the strain measurements. To verify that hoop strain does not change over different geometries, a series of preliminary FEA tests are computed involving different shapes and sizes as well as different loading conditions. Using COMSOL, the first series of preliminary FEA studies involve a simplistic 2D circular skull modeling four different geometric shapes on the inner wall of the skull shown in Figure 11. COMSOL has both the capability to create geometries within its own software or import geometries from external computer aided design programs. All of the models used in the 2D finite element analysis are created with SolidWorks, a 3D software package by Dassault Systèmes SolidWorks Corp[33].

![Figure 11. 2D circular model with different asymmetries on inner wall of the skull.](image)

The models in Figure 11 are labeled from top left to bottom right as: no asymmetry, small asymmetry, medium asymmetry, and large asymmetry. The second set of geometries used for the 2D FEA consists of the same four asymmetries shown in Figure 11, however
each asymmetry is applied to a model with a different size head circumference. The head circumferences correspond to an anthropometric survey of adults in [34, 35]. For the preliminary studies, the four adult head circumferences are based on a percentile scale of all the adults measured in the anthropometric survey [34, 35]. A percentile scale is described as the value of a variable below a certain percent of observations fall. For instance, the 95th percentile male (16.38 cm circumference) is the value of the head circumference that 95% of the people surveyed will fall below. The four head circumferences used are 16.38 cm representing the 95th percentile male, 15.47 cm representing the 50th percentile male, 14.47 cm representing the 5th percentile male, and 13.69 cm representing the 5th percentile female [34-36]. The latter two percentiles also closely resemble a 22.7 kg child and a 13.6 kg child, respectively. Figure 12 displays a comparison of the different head sizes that are modeled.

![Figure 12](image)

**Figure 12.** Four different head size models from: 95th% male, 50th% male, 5th% male, 5th% female (top left to bottom right).

Table 1 lists the size characteristics of each model skull along with the material properties of the brain and skull [37]. Therefore, the first set of 2D preliminary models consists of four different asymmetries at four different head sizes totaling 16 different geometries. After creating these geometries, the material properties are assigned to each geometry. Because the first set of 2D models is simplistic, the only material property assigned is the skull. COMSOL has built in material properties for common materials such as metals and plastics. However, for modeling a skull, the material properties must be inputted manually and customized. These values are found in Table 1. The same skull density, Young’s modulus, and Poisson’s ratio is used throughout the study.
There is only one physics involved when modeling the 2D preliminary FEA. Because the main objective is to find the hoop strain, the solid-mechanics module is chosen. Choosing the right boundary conditions allows the model to behave similarly to real world applications. Since this is a 2D model, the boundary condition needs to be fixed on outer diameter where \( x = 0 \) and \( y = \text{outer diameter} \). To allow the model to expand and behave realistically, this point is free to move in the \( y - \text{plane} \) but cannot move in the \( x - \text{plane} \). Creating another boundary condition at \( y = 0 \) and \( x = \text{diameter} \), this constrains the whole model properly and does not allow any floating or translation errors. The load associated with the 2D FEA is a single boundary load on the inner wall of the skull. Each of the 16 simplistic skull simulations is modeled at four different internal pressures: 500Pa, 1000Pa, 1500Pa, and 2000Pa. These pressures simulate a normal ICP level to a dangerously increasing ICP level that can cause permanent damage.

**Table 1.** Characteristics of different head sizes for preliminary studies.

<table>
<thead>
<tr>
<th>Head Size</th>
<th>Model Components</th>
<th>Dimensions (cm)</th>
<th>Young’s Modulus (Pa)</th>
<th>Poisson’s ratio</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95th % Male</td>
<td>Skull</td>
<td>O.D. = 16.38</td>
<td>(6.5 \times 10^9)</td>
<td>.22</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>Brain</td>
<td>I.D. = 14.73</td>
<td>(6.67 \times 10^4)</td>
<td>.48</td>
<td>1040</td>
</tr>
<tr>
<td>50th % Male</td>
<td>Skull</td>
<td>O.D. = 15.47</td>
<td>(6.5 \times 10^9)</td>
<td>.22</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>Brain</td>
<td>I.D. = 13.82</td>
<td>(6.67 \times 10^4)</td>
<td>.48</td>
<td>1040</td>
</tr>
<tr>
<td>5th % Male or 22.7kg Child</td>
<td>Skull</td>
<td>O.D. = 14.47</td>
<td>(6.5 \times 10^9)</td>
<td>.22</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>Brain</td>
<td>I.D. = 12.82</td>
<td>(6.67 \times 10^4)</td>
<td>.48</td>
<td>1040</td>
</tr>
<tr>
<td>5th % Female or 13.6kg Child</td>
<td>Skull</td>
<td>O.D. = 13.69</td>
<td>(6.5 \times 10^9)</td>
<td>.22</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>Brain</td>
<td>I.D. = 12.04</td>
<td>(6.67 \times 10^4)</td>
<td>.48</td>
<td>1040</td>
</tr>
</tbody>
</table>

Once all the loads, boundary conditions, and material properties are assigned, a mesh is created to allocate where the solver finds the solutions. For the simple model, a free tetrahedral mesh with “fine” components is sufficient. To verify this, an iterative process involves finding solutions with “coarser”, “coarse”, “fine”, and “finer” meshes. From this iterative process, the negligible difference between a “finer” and “fine” mesh is not worth the computational cost associated with using a “finer” mesh. Lastly, COMSOL requires a study to be chosen in order to find a solution. In this method, a stationary solver is used since the loads are static pressures and a time-dependent model is not needed to verify the behavior of hoop strain.

The next step involves adding a “brain” component to the 2D preliminary model. Using the previous models, the empty space inside the skull is replaced by a brain component. Therefore, the next series of 2D preliminary FEA geometries have the same four different asymmetries with four different head sizes totally another 16 geometries. Since the new set of models incorporates a brain component, a new material property is added into COMSOL. The Young’s modulus, the Poisson’s ratio, and density of the brain is also...
seen in Table 1. For all 16 models with the brain component, the boundary conditions stay the same as well as the pressure loads. Figure 13 displays the 2D models with the brain component highlighted in purple. The previous mesh as well as the stationary solver remains adequate for the 2D preliminary FEA studies with the brain.

![Figure 13. 2D circular model with brain and different asymmetries on inner wall of skull.](image)

The second series of FEA models include the same format as the previous 2D simplistic circular geometry. However, the second series has a more realistic geometry to verify that the hoop strain obtains the ability to integrate out the asymmetries regardless of overall geometry. In order to make the geometry more realistic, the length of the skull and the breadth of the skull are taken into account. Table 2 displays the values for the various lengths and breadths of different head sizes used to create the realistic model. Known averages for the length and breadth [34-36] set the boundaries of the realistic model but the curvature of the skull are estimated values. Figure 14 displays the 2D realistic models for varying skull sizes.

<table>
<thead>
<tr>
<th>Table 2. Various percentile values of human head length and breadth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size</strong></td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Length (cm)</td>
</tr>
<tr>
<td>Breadth (cm)</td>
</tr>
</tbody>
</table>
Figure 14. Length and breadth dimensions for 2D realistic model for four different head size models from: 95th% male, 50th% male, 5th% male, 5th% female (top left to bottom right).

Similar to the 2D circular model, the 2D realistic model includes 16 different geometries. The four different head sizes in Figure 14 each have four different asymmetries. The varying asymmetries resemble the systematic approach of the first geometry with no asymmetry, the second with small asymmetry, the third with medium asymmetry, and the fourth with large asymmetry. Figure 15 displays the four asymmetries that are involved in the 2D realistic FEA. Within COMSOL, the same procedures take place for both sets of 2D geometries. The physics module is repeated using solid-mechanics and also uses the same boundary conditions and loads. The pressures induced into the system remain the same using 500 Pa, 1000 Pa, 1500 Pa, and 2000 Pa. Furthermore, the mesh created involves a “fine” tetrahedral mesh with a stationary solver.

The final series of 2D FEA involves using the same realistic geometry, but this time adding the same “brain” component to the 2D preliminary model. The brain component fills up the interior space inside the skull just as before. Since the brain material properties have now been customized into COMSOL, there is no need to make a new material for the brain component. The Young’s modulus, the Poisson’s ratio, and density of the brain from Table 1 is used for the 2D realistic models as well. For all 16 models with the brain component, the boundary conditions, pressure loads, and solver stay the same. A new mesh is created to incorporate the brain component. Figure 16 displays the 2D models with the brain component highlighted in purple.
Figure 15. 2D realistic model with different asymmetries on inner wall of skull.

Figure 16. 2D realistic model with brain and different asymmetries on inner wall of skull.
3.1.2 Results of 2D Preliminary Finite Element Analysis

After running all the 2D finite element models in a systematic approach, COMSOL has the ability to output hoop strain with very little extra post processing needed. Once the model has run through the solver, the analyst has the ability to choose which data is to be observed. In this study, the main purpose is to observe the hoop strain. In order to do this, a 2D plot showing where all the strains occurred is accessed. Because the amount of plots produced from this study is extensive, only one head size is displayed in the following figures. The reason for this is that the different head sizes mainly affect the magnitudes of the strains rather than location. The following figures come from the 95th % male size skull with all four different asymmetries with and without the brain. Furthermore, each of the figures shows the strain distribution of the model affected by an interior pressure of 500 Pa.

Figure 17. First principal strain for 2D circular model with no asymmetry at 500 Pa.
**Figure 18.** First principal strain for 2D circular model with small asymmetry at 500 Pa.

**Figure 19.** First principal strain for 2D circular model with medium asymmetry at 500 Pa.
Figure 20. First principal strain for 2D circular model with large asymmetry at 500 Pa.

Figure 21. First principal strain for 2D circular model with brain and no asymmetry at 500 Pa.
**Figure 22.** First principal strain for 2D circular model with brain and small asymmetry at 500 Pa.

**Figure 23.** First principal strain for 2D circular model with brain and medium asymmetry at 500 Pa.
Figure 24. First principal strain for 2D circular model with brain and large asymmetry at 500 Pa.

Figure 25. First principal strain for 2D realistic model with no asymmetry at 500 Pa.
Figure 26. First principal strain for 2D realistic model with small asymmetry at 500 Pa.

Figure 27. First principal strain for 2D realistic model with medium asymmetry at 500 Pa.
Figure 28. First principal strain for 2D realistic model with large asymmetry at 500 Pa.

Figure 29. First principal strain for 2D realistic model with brain and no asymmetry at 500 Pa.
**Figure 30.** First principal strain for 2D realistic model with brain and small asymmetry at 500 Pa.

**Figure 31.** First principal strain for 2D realistic model with brain and medium asymmetry at 500 Pa.
From these figures, the strain distribution shows exactly where the maximum and minimum strain locations are. For the finite element models with the brain component, most of the strain occurs in the brain region. The reason for this is because when the skull slightly deforms, the brain, being much more flexible and soft, experiences more strain and deformations than the skull. The strain levels inside the brain almost “wash out” any strain indication on the outer edge of the skull. However, there is a small amount of strain that occurs and is discussed and compared to the hoop strain acquired from Fourier’s analysis.

3.1.3 Introduction of 3D Preliminary Finite Element Analysis

The last two preliminary sets of FEA simulations involve the same procedure using the same 2D circular and 2D realistic geometry, however, they are now translated into a 3D model. The preliminary 3D model is used to verify the same results that the hoop strain measured will integrate out all the asymmetries of the skull. The 3D circular model and 3D realistic model geometries are also created using SolidWorks[33]. In order to translate the 2D circular geometry into a 3D geometry, the 2D geometry is swept in 180 degrees in order to create a half sphere-like skull. For the realistic model, data from anthropometry measurements are used to translate the 2D realistic skull into a 3D realistic skull. As seen in section 9 of Figure 33, the vertical distance from the center of the eyes, known as the sellion, and the top of the head is used to translate the 2D realistic model into a 3D realistic model[38].
Figure 33. Anthropometry Measurements for 3D Realistic Model

Figure 34 and Figure 35 represent the 3D circular geometry used during the first set of 3D FEA studies. Similar to the 2D studies, the brain component is seen highlighted in purple within Figure 35. Figure 36 and Figure 37 represent the 3D realistic geometry used during the second set of 3D FEA studies. Again, the brain component is seen highlighted in purple within Figure 37.

![Figure 33](image-url)  
9 **Sellion to top of head.** The vertical distance from the nasal root depression between the eyes (sellion), to the level of the top of the head, measured with a headboard.  

<table>
<thead>
<tr>
<th>Sample</th>
<th>1st</th>
<th>5th</th>
<th>50th</th>
<th>95th</th>
<th>99th</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Men</td>
<td>cm</td>
<td>9.7</td>
<td>10.1</td>
<td>11.2</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>(in)</td>
<td>(3.8)</td>
<td>(4.0)</td>
<td>(4.4)</td>
<td>(4.9)</td>
</tr>
<tr>
<td>B Women</td>
<td>cm</td>
<td>9.0</td>
<td>9.5</td>
<td>10.5</td>
<td>11.7</td>
</tr>
<tr>
<td></td>
<td>(in)</td>
<td>(3.5)</td>
<td>(3.5)</td>
<td>(4.1)</td>
<td>(4.6)</td>
</tr>
</tbody>
</table>

Figure 34. 3D circular model with varying asymmetries on inner wall of skull.
Figure 35. 3D circular model with brain and varying asymmetries on inner wall of skull.

Figure 36. 3D realistic model with varying asymmetries on inner wall of skull.
Using these geometries for the 3D FEA, the physics chosen in COMSOL is solid-mechanics. The boundary condition allowed for expansion in the x, and y direction but did not allow the model to move in the z direction at point \((x = \text{outer diameter}, y = 0, \text{and } z = 0)\). This allowed the model to expand in all directions but not translate and float away in the z direction. The pressure load consists of the same varying pressures of 500 Pa, 1000 Pa, 1500 Pa, and 2000 Pa on the inner wall of the skull. To mesh all the elements together into a structure, a free tetrahedral “fine” mesh is used. Finally, a stationary solver is selected to compute the hoop strains of the structure.

3.1.4 Results of 3D Preliminary Finite Element Analysis

After setting up the 3D finite element models and running the solvers, COMSOL outputs the first principle strain distribution for each simulation. In order to calculate the hoop strain of the models in COMSOL, the first principle strain is integrated along the length of the circumference. Because an extensive amount of simulations are run, the following figures focus solely on the 3D circular and 3D realistic models simulated at 500 Pa. The following figures also display with and without the brain component for all four varying asymmetries.
Figure 38. First principal strain for 3D circular model with no asymmetry at 500 Pa.

Figure 39. First principal strain for 3D circular model with small asymmetry at 500 Pa.
Figure 40. First principal strain for 3D circular model with medium asymmetry at 500 Pa.

Figure 41. First principal strain for 3D circular model with large asymmetry at 500 Pa.
Figure 42. First principal strain for 3D circular model with brain and no asymmetry at 500 Pa.

Figure 43. First principal strain for 3D circular model with brain and small asymmetry at 500 Pa.
Figure 44. First principal strain for 3D circular model with brain and medium asymmetry at 500 Pa.

Figure 45. First principal strain for 3D circular model with brain and large asymmetry at 500 Pa.
Figure 46. First principal strain for 3D realistic model with no asymmetry at 500 Pa.

Figure 47. First principal strain for 3D realistic model with small asymmetry at 500 Pa.
Figure 48. First principal strain for 3D realistic model with medium asymmetry at 500 Pa.

Figure 49. First principal strain for 3D realistic model with large asymmetry at 500 Pa.
Figure 50. First principal strain for 3D realistic model with brain and no asymmetry at 500 Pa.

Figure 51. First principal strain for 3D realistic model with brain and small asymmetry at 500 Pa.
Figure 52. First principal strain for 3D realistic model with brain and medium asymmetry at 500 Pa.

Figure 53. First principal strain for 3D realistic model with brain and large asymmetry at 500 Pa.
When comparing the 2D models and 3D models, the strain distributions are relatively the same. However, the difference lies in the magnitude of the actual strains. The strains for the 3D models are actually 62% smaller than the strains in the 2D models. The reason this occurs is because the addition of the top portion of the skull in the 3D model stiffens and constrains the skull. This allows for less deflection, which in turn means less strain.

3.2 Fourier Analysis

In order to ensure that the COMSOL model is outputting the correct hoop strain, a Fourier analysis study is completed. By using COMSOL, the local strain is calculated at each point on the outer edge of the model. Figure 54 shows the location of the local strains retrieved from the 2D circular model and 3D circular model while Figure 55 displays the location of local strains for the 2D and 3D realistic models. The local strain is calculated at a total of 180 individual points.

![Figure 54. Location of local strains on circular model.](image)

![Figure 55. Location of local strains on realistic model.](image)

These local strains are then used to calculate the Fourier coefficients. Equations (23) and (24) have been rewritten into,
\[ a_n = \frac{1}{m} \sum_{i=1}^{m} \left[ \epsilon(\theta_i) \cos(n\theta_i) \Delta \theta \right]; \quad n \geq 0 \quad (27) \]

\[ b_n = \frac{1}{m} \sum_{i=1}^{m} \left[ \epsilon(\theta_i) \sin(n\theta_i) \Delta \theta \right]; \quad n \geq 1 \quad (28) \]

where the variable \( m \) represents the number of local points, \( \theta_i \) is the angle of each point, and \( \epsilon(\theta_i) \) is the strain at each local point. Using these Fourier coefficients, the hoop strain through Fourier analysis is,

\[ \epsilon(\theta) = a_0 + \sum [a_n \cos(n\theta_i) \Delta \theta + b_n \cos(n\theta_i) \Delta \theta] \quad (29) \]

Fourier analysis is performed on all of the same simulations that were completed through COMSOL.

3.3 Preliminary Discussions and Results – FEA vs. Analytic

3.3.1 2D Preliminary FEA vs. Analytic Results

As discussed before, the main purpose of this thesis is to utilize the hoop strain in order to measure the intracranial pressure. Since the shape of the skull is unique from one person to another, the hoop strain must be able to integrate out all asymmetries. The following tables show the results of the 2D preliminary hoop strains retrieved from COMSOL versus the hoop strain from Fourier’s Analysis.

**Table 3.** Hoop strain results from COMSOL vs. Fourier analysis for 95\(^{th}\)% male 2D circular skull.

<table>
<thead>
<tr>
<th>Test A1 - 2D Circular Skull 95(^{th}) Male</th>
<th>Symmetric</th>
<th>Small Asymmetry</th>
<th>Medium Asymmetry</th>
<th>Large Asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fourier</td>
<td>6.50063E-07</td>
<td>7.20283E-07</td>
<td>6.80283E-07</td>
</tr>
<tr>
<td>1000 Pa</td>
<td>Comsol</td>
<td>1.30057E-06</td>
<td>1.40530E-06</td>
<td>1.39360E-06</td>
</tr>
<tr>
<td></td>
<td>Fourier</td>
<td>1.30013E-06</td>
<td>1.40057E-06</td>
<td>1.39124E-06</td>
</tr>
<tr>
<td>1500 Pa</td>
<td>Comsol</td>
<td>1.95086E-06</td>
<td>2.18297E-06</td>
<td>2.10302E-06</td>
</tr>
<tr>
<td></td>
<td>Fourier</td>
<td>1.95020E-06</td>
<td>2.16086E-06</td>
<td>2.08686E-06</td>
</tr>
<tr>
<td>2000 Pa</td>
<td>Comsol</td>
<td>2.60115E-06</td>
<td>2.91062E-06</td>
<td>2.80402E-06</td>
</tr>
<tr>
<td></td>
<td>Fourier</td>
<td>2.60027E-06</td>
<td>2.88114E-06</td>
<td>2.7813E-06</td>
</tr>
</tbody>
</table>

**Table 4.** Hoop strain results from COMSOL vs. Fourier analysis for 50\(^{th}\)% male 2D circular skull.

<table>
<thead>
<tr>
<th>Test B1 - 2D Circular Skull 50(^{th}) Male</th>
<th>Symmetric</th>
<th>Small Asymmetry</th>
<th>Medium Asymmetry</th>
<th>Large Asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 Pa</td>
<td>Comsol</td>
<td>1.30057E-06</td>
<td>1.40530E-06</td>
<td>1.39360E-06</td>
</tr>
<tr>
<td></td>
<td>Fourier</td>
<td>1.30013E-06</td>
<td>1.40057E-06</td>
<td>1.39124E-06</td>
</tr>
<tr>
<td>1500 Pa</td>
<td>Comsol</td>
<td>1.95086E-06</td>
<td>2.18297E-06</td>
<td>2.10302E-06</td>
</tr>
<tr>
<td></td>
<td>Fourier</td>
<td>1.95020E-06</td>
<td>2.16086E-06</td>
<td>2.08686E-06</td>
</tr>
<tr>
<td>2000 Pa</td>
<td>Comsol</td>
<td>2.60115E-06</td>
<td>2.91062E-06</td>
<td>2.80402E-06</td>
</tr>
<tr>
<td></td>
<td>Fourier</td>
<td>2.60027E-06</td>
<td>2.88114E-06</td>
<td>2.7813E-06</td>
</tr>
</tbody>
</table>
Table 5. Hoop strain results from COMSOL vs. Fourier analysis for 5th% male 2D circular skull.

<table>
<thead>
<tr>
<th>TestC1 - 2D Circular Skull 5% Male - 22.7 kg Child</th>
<th>Symmetric</th>
<th>Small Asymmetry</th>
<th>Medium Asymmetry</th>
<th>Large Asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comsol</td>
<td>Fourier</td>
<td>Comsol</td>
<td>Fourier</td>
<td>Comsol</td>
</tr>
<tr>
<td>500 Pa</td>
<td>5.61584E-07</td>
<td>5.61349E-07</td>
<td>5.50413E-07</td>
<td>5.50985E-07</td>
</tr>
<tr>
<td>1000 Pa</td>
<td>1.12317E-06</td>
<td>1.12270E-06</td>
<td>1.10483E-06</td>
<td>1.10197E-06</td>
</tr>
<tr>
<td>1500 Pa</td>
<td>1.68475E-06</td>
<td>1.68405E-06</td>
<td>1.65724E-06</td>
<td>1.65296E-06</td>
</tr>
<tr>
<td>2000 Pa</td>
<td>2.24634E-06</td>
<td>2.24540E-06</td>
<td>2.20965E-06</td>
<td>2.20394E-06</td>
</tr>
</tbody>
</table>

Table 6. Hoop strain results from COMSOL vs. Fourier analysis for 5th% female 2D circular skull.

<table>
<thead>
<tr>
<th>TestD1 - 2D Circular Skull 5% Female - 13.6 kg Child</th>
<th>Symmetric</th>
<th>Small Asymmetry</th>
<th>Medium Asymmetry</th>
<th>Large Asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comsol</td>
<td>Fourier</td>
<td>Comsol</td>
<td>Fourier</td>
<td>Comsol</td>
</tr>
<tr>
<td>1000 Pa</td>
<td>1.05071E-06</td>
<td>1.05024E-06</td>
<td>1.08005E-06</td>
<td>1.07784E-06</td>
</tr>
<tr>
<td>1500 Pa</td>
<td>1.57607E-06</td>
<td>1.57536E-06</td>
<td>1.62007E-06</td>
<td>1.61676E-06</td>
</tr>
<tr>
<td>2000 Pa</td>
<td>2.10143E-06</td>
<td>2.10047E-06</td>
<td>2.16010E-06</td>
<td>2.15568E-06</td>
</tr>
</tbody>
</table>

Looking at Table 3, the behavior is very systematic and repetitive. Focusing on each separate pressure input, at 500 Pa, the average difference between the COMSOL results vs. the Fourier analysis results is 0.097%. The average percent difference between the varying asymmetries at 500 Pa is 7.41%. This percent difference between varying asymmetries is negligible considering the change in strain from an increase in pressure of 500 Pa to 1000 Pa is 100.02%. Most notably, a change from a normal ICP, around 1000 Pa, to a more dangerous level of ICP, 2000 Pa, displays a percent difference of also 99.98%. Therefore, the 7.41% difference is negligible compared to the change in strain that you will see associated with increased ICP. Table 4, Table 5, and Table 6 display the results for the same 2D circular model, but with head sizes of 50th% male, 5th% male, and 5th% female respectively. Table 7 displays the results from these measurements and the similarities between them.

Table 7. Comparison Results of Fourier Analysis vs. COMSOL 2D Circular Model

<table>
<thead>
<tr>
<th>Comparison Results of Fourier Analysis vs Comsol 2D Circular Model</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percent Difference Between COMSOL and Fourier Analysis</td>
<td>0.097%</td>
<td>0.065%</td>
<td>0.099%</td>
<td>0.087%</td>
</tr>
<tr>
<td>Average Percent Difference Between Various Asymmetries</td>
<td>7.41%</td>
<td>5.36%</td>
<td>3.65%</td>
<td>4.99%</td>
</tr>
<tr>
<td>Average Percent Difference between 1000 Pa vs. 2000 Pa</td>
<td>99.98%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Since exporting all the comparisons for each test run will be rather extensive and repetitive, this study preliminary study will focus on the average percent difference for the overall of each preliminary study.
Table 8. Comparison results of Fourier analysis vs. COMSOL 2D circular model with brain.

<table>
<thead>
<tr>
<th>Comparison Results of Fourier Analysis vs Comsol 2D Circular Model with Brain</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percent Difference between COMSOL and Fourier Analysis</td>
<td>0.11%</td>
<td>0.47%</td>
<td>0.24%</td>
<td>0.25%</td>
</tr>
<tr>
<td>Average Percent Difference Between Various Asymmetries</td>
<td>6.91%</td>
<td>5.48%</td>
<td>3.82%</td>
<td>5.05%</td>
</tr>
<tr>
<td>Average Percent Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 9. Comparison results of Fourier analysis vs. COMSOL 2D realistic model.

<table>
<thead>
<tr>
<th>Comparison Results of Fourier Analysis vs Comsol 2D Realistic Model</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percent Difference between COMSOL and Fourier Analysis</td>
<td>1.10%</td>
<td>1.55%</td>
<td>0.97%</td>
<td>1.09%</td>
</tr>
<tr>
<td>Average Percent Difference Between Various Asymmetries</td>
<td>2.46%</td>
<td>4.81%</td>
<td>3.99%</td>
<td>8.69%</td>
</tr>
<tr>
<td>Average Percent Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 10. Comparison results of Fourier analysis vs. COMSOL 2D realistic model with brain.

<table>
<thead>
<tr>
<th>Comparison Results of Fourier Analysis vs Comsol 2D Realistic Model with Brain</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percent Difference between COMSOL and Fourier Analysis</td>
<td>1.13%</td>
<td>1.48%</td>
<td>1.13%</td>
<td>1.09%</td>
</tr>
<tr>
<td>Average Percent Difference Between Various Asymmetries</td>
<td>2.27%</td>
<td>4.72%</td>
<td>4.34%</td>
<td>8.66%</td>
</tr>
<tr>
<td>Average Percent Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

The average overall percent difference between all the 2D simulations is seen in Table 11. The average percent difference between the varying asymmetries for all 2D simulations range from 3.95% to 6.85% depending on which size skull is used. This percent difference describes the change in strain from a skull with no asymmetries to a skull having small, medium, and large asymmetries. The average percent difference between a normal ICP of 1000 Pa to a dangerously increased ICP of 2000 Pa is 100%. This result concludes that the strain is directly proportional to the ICP. As the pressure on the inside of the skull doubles in value, the strain will also double in value. That is why the percent difference is seen to be 100%. Since the percent difference for varying asymmetries is so small with respect to the percent different for varying pressures, it is safe to assume that the change in asymmetry is negligible.

Table 11. Overall comparison results for all 2D preliminary studies, Fourier analysis vs. COMSOL.

<table>
<thead>
<tr>
<th>Overall Comparison Results of Fourier Analysis vs Average Comsol 2D Simulations</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Average % Difference between COMSOL and Fourier Analysis</td>
<td>0.61%</td>
<td>0.89%</td>
<td>0.61%</td>
<td>0.63%</td>
</tr>
<tr>
<td>Overall Average % Difference Between Various Asymmetries</td>
<td>4.76%</td>
<td>5.09%</td>
<td>3.95%</td>
<td>6.85%</td>
</tr>
<tr>
<td>Overall Average % Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
3.3.2 3D Preliminary FEA vs. Analytic Results

The results between the 3D finite element analysis versus the analytical analysis displays similar comparisons to the 2D simulations. The following tables display the percent difference between COMSOL vs. Fourier analysis, varying asymmetries, and varying pressures. Looking at the overall comparison for all 3D simulations in Table 16, the average percent difference between all the models are in the range of 3.04% to 5.71%. The 3D simulations also show a 100% difference between doubling in pressure as expected. These results provide the same conclusion in which the change in asymmetries is negligible in comparison to the change in pressure.

Table 12. Comparison results of Fourier analysis vs. COMSOL 3D circular model.

<table>
<thead>
<tr>
<th>Comparison Results of Fourier Analysis vs Comsol 3D Circular Model</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percent Difference Between COMSOL and Fourier Analysis</td>
<td>0.65%</td>
<td>1.17%</td>
<td>0.66%</td>
<td>0.97%</td>
</tr>
<tr>
<td>Average Percent Difference Between Various Asymmetries</td>
<td>5.73%</td>
<td>5.73%</td>
<td>2.13%</td>
<td>5.54%</td>
</tr>
<tr>
<td>Average Percent Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 13. Comparison results of Fourier analysis vs. COMSOL 3D circular model with brain.

<table>
<thead>
<tr>
<th>Comparison Results of Fourier Analysis vs Comsol 3D Circular Model with Brain</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percent Difference Between COMSOL and Fourier Analysis</td>
<td>0.62%</td>
<td>1.31%</td>
<td>0.62%</td>
<td>1.07%</td>
</tr>
<tr>
<td>Average Percent Difference Between Various Asymmetries</td>
<td>5.37%</td>
<td>5.19%</td>
<td>2.12%</td>
<td>4.91%</td>
</tr>
<tr>
<td>Average Percent Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 14. Comparison results of Fourier analysis vs. COMSOL 3D realistic model.

<table>
<thead>
<tr>
<th>Comparison Results of Fourier Analysis vs Comsol 3D Realistic Model</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percent Difference Between COMSOL and Fourier Analysis</td>
<td>1.25%</td>
<td>1.59%</td>
<td>1.80%</td>
<td>1.20%</td>
</tr>
<tr>
<td>Average Percent Difference Between Various Asymmetries</td>
<td>5.34%</td>
<td>5.73%</td>
<td>4.01%</td>
<td>6.18%</td>
</tr>
<tr>
<td>Average Percent Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 15. Comparison results of Fourier analysis vs. COMSOL 3D realistic model with brain.

<table>
<thead>
<tr>
<th>Comparison Results of Fourier Analysis vs Comsol 3D Realistic Model with Brain</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percent Difference Between COMSOL and Fourier Analysis</td>
<td>1.35%</td>
<td>1.07%</td>
<td>1.78%</td>
<td>1.16%</td>
</tr>
<tr>
<td>Average Percent Difference Between Various Asymmetries</td>
<td>5.42%</td>
<td>4.49%</td>
<td>3.88%</td>
<td>6.23%</td>
</tr>
<tr>
<td>Average Percent Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 16. Overall comparison results for all 3D preliminary studies, Fourier analysis vs. COMSOL.

<table>
<thead>
<tr>
<th>Overall Comparison Results of Fourier Analysis vs Average Comsol 3D Simulations</th>
<th>95th % Male</th>
<th>50th % Male</th>
<th>5th % Male or 22.7 kg Child</th>
<th>5th % Female or 13.6 kg Child</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Average % Difference Between COMSOL and Fourier Analysis</td>
<td>0.97%</td>
<td>1.28%</td>
<td>1.21%</td>
<td>1.10%</td>
</tr>
<tr>
<td>Overall Average % Difference Between Various Asymmetries</td>
<td>5.47%</td>
<td>5.28%</td>
<td>3.04%</td>
<td>5.71%</td>
</tr>
<tr>
<td>Overall Average % Difference between 1000 Pa vs. 2000 Pa</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
To further verify that measuring the hoop strain integrates out all asymmetries, a spatial decomposition is performed on the 2D circular model with small asymmetries. The main purpose of displaying the spatial decomposition is to demonstrate that the magnitude of strain within the first mode dominates all of the other individual modes. Equation (30) displays the formula used in MATLAB, a technical computing software, to plot modes of the 2D structure. Figure 56, displays the first mode at 1000 Pa. The strain magnitude of the first mode is approximately $6.34 \times 10^{-7}$.

$$h = \text{polar}(\theta, A_n l \cos(\theta i))$$  

(30)

Figure 56. Spatial decomposition for first mode of 2D circular model.

The magnitude of strain for the next three modes are approximately $8.04 \times 10^{-8}$, $3.30 \times 10^{-8}$, and $8.05 \times 10^{-9}$. The first mode is approximately 7.89 times larger than the second mode. Figure 57 displays the mode shapes for the second, third, and fourth mode. Figure 58 shows how much larger the first mode is with respect to the second, third, and fourth mode.
Figure 57. Spatial decomposition for modes 2-4 of 2D circular model.

Figure 58. Spatial decomposition for modes 1-4 of 2D circular model.
Chapter 4. Experimental Data Collection of PVC/3D Printed Test Rig

4.1 Goal of Experimental Data Collection

The purpose of the experimental tests is to validate the COMSOL finite element model by acquiring the PCB Piezotronic’s hydrophone response and piezoelectric PVDF wire sensor response due to an input pressure. The output response of both sensors is measured in voltages. The PCB Piezotronic’s hydrophone voltages are converted into pressure using the manufacturer’s calibration factor. However, since the piezoelectric PVDF wire sensor has an unknown \( \frac{\text{volts}}{\text{pressure}} \) calibration factor, COMSOL is used to obtain this unknown value. Therefore, the piezoelectric PVDF wire sensor voltages are combined with finite element results in Chapter 5 to validate the measured pressure of the hydrophone versus the measured pressure of the piezoelectric PVDF wire sensor.

4.2 Description of Experimental Test Setup

4.2.1 Description of PVC and 3D Printed Test Articles

The initial experimental testing is done on a custom PVC test article. This article consists of a 6” clear PVC pipe with one end enclosed with a flat end cap and the other end enclosed with a round end cap. The end caps are secured to the 6” clear PVC pipe using PVC gorilla cement. In order to measure the pressure on the inside of the PVC test article, a hole is drilled and tapped into the clear 6” PVC section. A PCB Piezotronics hydrophone is inserted into the tapped hole. Additionally, two more holes are drilled and tapped into the PVC test article. The first additional hole is tapped into the clear PVC section of the test article to allow for an inlet water flow. The second additional hole is tapped at the top of the rounded end cap for an outlet water flow. Placing the outlet at the top of the test article helps remove any existing air bubbles within the test article. Figure 59 shows the PVC test article with described holes drilled and tapped in the clear PVC section. An extra third hole can be seen in Figure 59, which is unused and plugged with a metal stopper.
The second experimental tests are performed on three separate 3D printed test articles. For the purpose of this study, the focus is on a 70% scaled version of the 3D circular model for the 95th % male skull used in the preliminary tests. After scaling the 95th % male skull as used in[37], the outer diameter of the 3D printed test articles are 12.36cm. Unlike the preliminary model where only half the skull was modeled, the test article is made up of a fully enclosed sphere. Each test article involves two matched hemispheres created initially from SolidWorks as seen in Figure 60.

Figure 59. Polyvinylchloride (PVC) test article used in initial experimental testing.

Figure 60. SolidWorks model to be extruded using 3D printer. (Rows Top to Bottom: small asymmetry, medium asymmetry, large asymmetry)
There are six total hemispheres used to create three fully enclosed spheres representing the three different asymmetries: small, medium, and large. Within SolidWorks, the model is converted into an STL (Stereolithography) file, which is a file that describes only the outer surface layer of the model as an assembly of meshed triangles[39]. The STL files are then extruded into a physical test article by using a 3D printer. The 3D printer extracts the STL file layer by layer and extrudes the solid model onto a platform. This process is also known as additive manufacturing[40]. Again, since printing the actual size of the 95th % male skull is time costly, the model is scaled down to 70% of the original size. Figure 61 displays the extruded 3D printed test articles created from the additive manufacturing process.
Figure 61. Extruded 3D printed test article through additive manufacturing processes. (a) Small asymmetry. (b) Medium asymmetry. (c) Large asymmetry.

Since the process of additive manufacturing extrudes the test article layer by layer, the hemispheres are not complete solids. In order to prevent water leaks from testing, each of the hemispheres are coated with a flexible rubber coating to prevent leaks. Then each hemisphere is attached to its corresponding hemisphere with a very thin layer of epoxy. The final test article is then sprayed with another layer of flexible rubber coating to help prevent leaks as well as keeping a uniform outer finish to allow for complete attachment of the PVDF wire. Lastly, the extruded 3D printed test articles are drilled and tapped, similarly to the PVC test article. The three drilled and tapped holes serve the same functions as the PVC test article: inlet water flow, outlet for water flow, and for attachment of hydrophone to measure inside pressure. The measured hydrophone pressure is used to see how accurately the PVDF wire measures the inside pressure.
Figure 62. Extruded 3D printed test article treated with multiple layers of rubber flexible coating. (a) Small asymmetry. (b) Medium asymmetry. (c) Large asymmetry.

4.2.2 Description of Experimental Test Setup and Procedures

The main goal of the test rig is simulate an intracranial pressure on the inside of the skull by applying a pulsating pressure on the inside the test articles. In order to do this, a diaphragm pump is used to circulate water through vinyl tubing connected to the test article. From the test article, water flows through an outlet and into a water vessel or water tower. The water vessel stores the water that is supplied to the diaphragm pump and also allows for easy filling and emptying of fluid from the whole system. The diaphragm pump is powered by a varying voltage source. To increase the speed of the pump and thus the frequencies of the pulsations, the voltage is increased on the power source. The voltages applied to the diaphragm pump consist of 2 volts, 3 volts, and 5 volts.

The piezoelectric PVDF wire sensor is attached to the test article using Scotch double-sided tape. To fix the boundary conditions on the end, blue painters tape is fastened to the ends of the PVDF wire sensor to help secure the sensor to the test article. The PVDF wire wraps around the PVC test article with three complete turns and only two turns for the 3D printed test article as shown in Figure 63.
Figure 63. Close up of piezoelectric PVDF wire sensor on test articles. (a) PVC test article with 3 turns. (b) 3D printed test article with 2 turns.

The piezoelectric PVDF wire sensor connects to a custom charge amplifier to convert the charge of the PVDF wire into voltage as shown in Figure 64. The custom charge amplifier is then connected to a National Instruments data acquisition device.

Figure 64. Custom charge amplifier used to convert charge into volts. (a) Top view. (b) Front View.

Figure 65. National Instruments data acquisition device with PCB Piezotronics hydrophone and the piezoelectric PVDF wire sensor connected.
The same National Instruments data acquisition device, Figure 65, is used to obtain data from the PCB Piezotronics hydrophone. All the data is then recorded and stored through a MATLAB GUI created and edited from the Vibrations and Acoustics Lab at Virginia Polytechnic Institute and State. Once the data is stored, post-processing techniques are applied using MATLAB to acquire the desired results. The complete experimental setups for the PVC test article and the 3D printed test articles are shown in Figure 66 and Figure 67 respectively.

Figure 66. Complete experimental test setup with PVC test article.

Figure 67. Complete experimental test setup with 3D printed test article.
4.3 Experimental Results for PVC and 3D Printed Test Articles

The two sets of data collected from the experimental tests are the PCB Piezotronic’s hydrophone voltages and the piezoelectric PVDF wire sensor voltages. The piezoelectric PVDF wire sensor voltages are used in conjunction with the COMSOL results to calculate the pressure measured from the PVDF wire sensor. In order to verify that the PVDF sensor measures the correct pressure, the hydrophone pressure is used as a baseline. Using the manufacturer’s calibration factor of the PCB Piezotronic’s hydrophone, the voltages collected from the NI-DAQ is converted into Pascal’s. The hydrophone calibration factor is $15.05 \times 10^{-6} \frac{V}{Pa}$. The PVC test article is used as a preliminary test to make sure the entire rig works properly. The tests were run at 2 Volts, 3 Volts, and 6 Volts for the PVC test article and 2 Volts, 3 Volts, and 5 Volts for the extruded 3D printed test articles. The PCB Piezotronic’s hydrophone pressures for the PVC test article as well as the 3D printed test articles are seen in the following figures. The voltages from the piezoelectric PVDF wire sensor are used in Chapter 5, once the calibration factor is calculated from COMSOL. Ideally, the pressure from the hydrophones will match the pressure from the PVDF sensor.

![Hydrophone Pressure on PVC Pipe Rig at 12V - Freq 10Hz-150Hz](image)

**Figure 68.** Measured hydrophone pressures for PVC test article with pump running at 2 volts.
Figure 69. Measured hydrophone pressures for PVC test article with pump running at 3 volts.

Figure 70. Measured hydrophone pressures for PVC test article with pump running at 6 volts.
Figure 71. Measured hydrophone pressures for 3D printed test article with small asymmetry at 2 volts.

Figure 72. Measured hydrophone pressures for 3D printed test article with small asymmetry at 3 volts.
Figure 73. Measured hydrophone pressures for 3D printed test article with small asymmetry at 5 volts.

Figure 74. Measured hydrophone pressures for 3D printed test article with medium asymmetry at 2 volts.
Figure 75. Measured hydrophone pressures for 3D printed test article with medium asymmetry at 3 volts.

Figure 76. Measured hydrophone pressures for 3D printed test article with medium asymmetry at 5 volts.
**Figure 77.** Measured hydrophone pressures for 3D printed test article with large asymmetry at 2 volts.

**Figure 78.** Measured hydrophone pressures for 3D printed test article with large asymmetry at 3 volts.
Figure 79. Measured hydrophone pressures for 3D printed test article with large asymmetry at 5 volts.
Chapter 5. COMSOL Finite Element Modeling of Experimental Test Rig

5.1 Goal of Experimental Data Collection

There are three main purposes for using COMSOL finite element modeling within this study. The first goal is to determine the unknown calibration factor, \( \frac{\text{volts}}{\text{pascal}} \), of the piezoelectric PVDF wire sensor for different size skulls. The second goal is to determine what physical attributes of the human skull affect this calibration factor. Based on the preliminary studies and results, the asymmetries within a structure will have minimal affect on the calibration factor of the piezoelectric PVDF wire sensor. The third goal of using COMSOL finite element modeling is to validate the outputted calibration factor by applying it to the experimental data in Chapter 4 and comparing the measured PCB Piezotronic’s hydrophone pressure to the piezoelectric PVDF wire sensor pressure.

5.2 Finite Element Model Setup

5.2.1 Geometry and Material Properties

In order to model both the physical structure of the test articles and the piezoelectric PVDF wire sensor, two separate models are created and then coupled together. The geometries for determining which attributes affect the calibration factor are based upon realistic thicknesses and head circumferences of a human skull. The first set of models has a constant thickness of 6 mm with varying circumferences. By keeping the thickness constant, if the calibration factor changes, then the calibration factor is dependent on circumference size. The geometries model circumferences from a 1 year old, 4 year old, and a 16 year old with head circumferences of 49.9 cm, 53 cm, and 57 cm respectively[41, 42]. Two additional head circumferences are added for a 5’ 6” adult with head circumference of 60 cm and a 6’ 3” adult with head circumference of 62 cm [41]. Figure 80 displays the 60 cm realistic skull with a top cut section and a side cut section. All of the other geometries are similar, but scaled down to allow for different size circumferences. The hollow region will be replaced with a brain-like material within COMSOL.
The second set of geometries consists of using a constant head circumference with changing interior thicknesses and asymmetries. The chosen head circumference is the 5’ 6” adult with a 60 cm skull circumference. The change in thickness varies from 5 mm, 6 mm, and 7 mm using random asymmetries on the inside. This set of geometries determines if thickness and asymmetry variation affects the calibration factor. Figure 81 displays the three geometries with different thicknesses and slight variations in asymmetry.
The last set of skull geometries imitates the 3D printed test articles from the experimental test runs. All of the skull geometries are modeled in three dimensions. The 3D printed test articles and skull geometries are not symmetric because of the different asymmetries on the inside wall where the brain is located. Therefore, all of the skull geometries need to be modeled in three-dimensional space. Since the 3D test articles are printed from a SolidWorks STL file, COMSOL has the ability to directly import the exact model that is printed out. Figure 84 shows an example of what the experimental skull geometry looks like from Chapter 4.
For modeling the PVC test article, the geometry that matches the dimensions of the physical structure is created inside of COMSOL using their geometry builder. To keep the model simple and efficient, the PVC test article is created in two dimensions. The PVC model does not need to be created with a 3D geometry because of its symmetry and a 2D model is able to accurately represent the PVC test article. Figure 85 displays the geometry for modeling the PVC test article. The symmetry lays on the left most edges of the geometry.

The geometry for the piezoelectric PVDF wire is derived from Measurement Specialties specification sheet[27]. The piezoelectric PVDF wire is made up of four layers: inner copper core, piezoelectric polymer, outer copper, and outer polyethylene jacket. The outer diameter of the entire PVDF wire sensor is 2.72 mm. The inner copper conductor
component has a diameter of 1.02 \text{mm}. The piezoelectric PVDF polymer material diameter is 1.2 \text{mm}. The overall circumference of the wire equally matches the outer circumference of the PVC test article or any of the skull geometries, depending on which simulation is run. The piezoelectric PVDF wire sensor geometry is built with the intention of one wrap around the test article. Figure 86 displays the geometry for the piezoelectric PVDF wire, which is created within SolidWorks and then imported into COMSOL.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure86}
\caption{Geometry for piezoelectric PVDF wire sensor in COMSOL. (a) Full. (b) Cross-section}
\end{figure}

The three main PVC material properties needed to solve the solid mechanics module are Poisson’s ratio, Young’s modulus, and the density which are \(0.41\), \(4.6 \times 10^9\ \text{Pa}\), and \(1420\ \text{kg/m}^3\) respectively[43-45]. The material used for creating the 3D printed test articles is an extruded ABS plastic. The material properties which represent ABS plastic for Poisson’s ratio, Young’s modulus, and density are \(0.41\), \(2 \times 10^5\ \text{Pa}\), and \(1060\ \text{kg/m}^3\) from [46]. Lastly, for modeling the piezoelectric PVDF wire, three materials are needed. Copper, which is located in COMSOL’s material library, has properties of \(0.35\) for Poisson’s ratio, \(110 \times 10^9\ \text{Pa}\) for Young’s modulus, and \(8700\ \text{kg/m}^3\) for density. The outer layer of the piezoelectric PVDF wire is made up of a polyethylene jacket with material properties of \(0.4\) for Poisson’s ratio, \(700 \times 10^6\ \text{Pa}\) for Young’s modulus, and \(958\ \text{kg/m}^3\) for density [47]. The material properties for the piezoelectric PVDF polymer comes directly from the manufacturer Measurement Specialties[48] and from [49]. The main properties for the piezoelectric polymer material are the compliance matrix, the coupling matrix, the relative permittivity, and the density of \(1780\ \text{kg/m}^3\). The following represents the compliance matrix, coupling matrix, and relative permittivity for the piezoelectric PVDF wire:
The behavior of the PV test article, 3D printed test article, and the piezoelectric PVDF sensor determines which boundary conditions to use. The additional realistic skull geometries have similar boundary conditions and loads as the 3D printed test articles. Starting with the physical structure, both test articles have an applied load on the inside wall of the structure. This load represents the water pressure pushing on the inside walls of the structure imitating intracranial pressure. The pressure loads for the PVC test article, 3D printed test articles, and realistic skull model are shown in Figure 87.

![Figure 87](image)

**Figure 87.** Mechanical boundary conditions applied as a pressure load. (a) PVC test article. (b) 3D printed test article. (c) Realistic skull model.

Another important aspect of the physical structures is creating an identity map to couple the deformations from the structure into the piezoelectric PVDF wire sensor. This
identity map is applied to a single point on the PVC test article and on the entire outer diameter of the 3D printed test articles. Both these points are the location of where the PVDF wire is attached during experimental analysis shown in Figure 88. Also shown in Figure 88 is the location where the coupling factor from hoop strain to pressure will be calculated for the realistic skull model. These deformations are then coupled to the inner edge of the piezoelectric PVDF wire. The assumption is made that the PVDF wire is perfectly attached to the structure on a single edge, which is shown in Figure 89(a). Figure 89(b) shows another boundary condition on the outside edge of the piezoelectric PVDF wire sensor. This boundary condition prescribes the displacement in the z-direction, preventing the wire from slipping in the vertical plane.

Figure 88. Mechanical boundary condition to couple the PVDF wire to the PVC and 3D printed structure. (a) Point on PVC. (b) Outer edge of 3D printed test article. (c) Outer edge of realistic skull model.

Figure 89. Mechanical boundary condition to couple the PVDF wire to the PVC and 3D printed structure. (a) Inner edge of PVDF wire. (b) Outer edge of PVDF wire.
The electrical boundary conditions associated with the piezoelectric material is grounding the copper conductor and also adding a discontinuity in the electrical materials of the piezoelectric PVDF wire sensor. Although the geometry of the PVDF wire sensor appears to be a closed loop, the discontinuity prevents the PVDF wire from behaving as a closed continuous electrical circuit.

The meshes for the PVC test article, 3D printed test article, and realistic skull model are created with COMSOL’s automated mesh function. Depending on the physics module interaction, COMSOL finds an ideal mesh for the problem. In most cases, creating a mesh this way is acceptable. Figure 90 shows the meshes for the PVC test article, 3D printed test article, and realistic skull model. However, sometimes the automated mesh causes problems. Therefore, a custom mesh is required which is the case for the piezoelectric PVDF wire sensor. The wire is broken up into two sections with a free triangular mesh on its face. Then using this mesh surface, a swept function meshes the entire domain of each section. Figure 91 shows the meshed surface, the meshed domains, and the final entire mesh of the piezoelectric PVDF wire.

![Figure 90. Automated mesh using COMSOL. (a) PVC test rig. (b) 3D printed test article. (c) Realistic skull model.](image)
As stated earlier, the finite element analysis is completed in two studies. The first model includes the physical structure; PVC test article and 3D printed test articles. Because this model only experiences an internal pressure load, only the solid mechanics module is involved for modeling. The study associated with the first model is the frequency response of the physical structure. In order to calculate the frequency response quicker, a modal study analysis is used in parallel with the frequency response solver. Since most of the response occurs at lower frequency from the experimental results, the main focus will by under 1kHz.

For the second finite element model, only a piezoelectric module is needed. Because the deformations are already solved for in the first model, COMSOL can recall the stored deformations solved earlier and then couple them into the piezoelectric model. The piezoelectric module makes use of the strain-charge constitutive relation to output a charge for any given strain. Again, the deformation is initially solved for in model 1 and then coupled into model 2.

5.3 COMSOL Modeling of Various Head Circumferences Results

Completing this COMSOL study analysis demonstrates that the calibration factor of the piezoelectric PVDF wire sensor is dependent on the overall circumference of the test article. The following four different size skull models are used to compare the calibration factors to overall circumference: 4 year old – 53 cm, 16 year old – 57 cm, 5’6” adult – 60 cm, and 6’ 3” adult – 62 cm. In order to directly compare the calibration factor to the circumference of the skull, the thickness is kept constant at 6mm throughout the testing. Table 17 shows the coupling factors that are associated with each calibration factor in Table 18 for each different sized skull model to be used with the PVDF wire sensor. Figure 92 displays a plot of the calibration factors with the integrated coupling factors computed from COMSOL. These results show that the calibration factor is dependent on
the overall circumference and displays a pattern of decreasing calibration factor with decreasing skull size.

Table 17. Coupling factor results for realistic skull model with changing circumference.

<table>
<thead>
<tr>
<th>Description of Model</th>
<th>Circumference Size (cm)</th>
<th>Coupling Factor ( \frac{\text{strain}}{\text{Pa}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult I</td>
<td>62 cm</td>
<td>( 8.46 \times 10^{-11} )</td>
</tr>
<tr>
<td>Adult II</td>
<td>60 cm</td>
<td>( 5.78 \times 10^{-11} )</td>
</tr>
<tr>
<td>16 Year Old</td>
<td>57 cm</td>
<td>( 4.87 \times 10^{-11} )</td>
</tr>
<tr>
<td>4 Year Old</td>
<td>53 cm</td>
<td>( 4.47 \times 10^{-11} )</td>
</tr>
</tbody>
</table>

Table 18. Calibration factor results for realistic skull model with changing circumference.

<table>
<thead>
<tr>
<th>Description of Model</th>
<th>Circumference Size (cm)</th>
<th>Calibration Factor ( \frac{\text{volts}}{\text{Pa}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult I</td>
<td>62 cm</td>
<td>( 3.37 \times 10^{-06} )</td>
</tr>
<tr>
<td>Adult II</td>
<td>60 cm</td>
<td>( 2.30 \times 10^{-06} )</td>
</tr>
<tr>
<td>16 Year Old</td>
<td>57 cm</td>
<td>( 1.94 \times 10^{-06} )</td>
</tr>
<tr>
<td>4 Year Old</td>
<td>53 cm</td>
<td>( 1.78 \times 10^{-06} )</td>
</tr>
</tbody>
</table>
5.4 COMSOL Modeling of Various Asymmetries and Thicknesses Results

Using the realistic skull geometries associated with the three varying thicknesses of 5 mm, 6 mm, and 7 mm, the output calibration factor for each scenario is seen in Figure 93. Although there appears to be some distinction between the calibration factors for each thickness, the result is actually negligible compared to the differences seen when the circumference changes. Table 19 displays the coupling factors associated with each calibration factor in Table 20 for each thickness variation. This result helps validate the initial assumption that the piezoelectric PVDF wire sensor is unaffected by interior asymmetries and thicknesses.

Table 19. Coupling factor results for realistic skull model with changing thickness and asymmetry.

<table>
<thead>
<tr>
<th>Description of Model</th>
<th>Thickness Size (mm)</th>
<th>Coupling Factor ($\text{strain/} \text{Pa}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model I</td>
<td>5 mm</td>
<td>$5.98 \times 10^{-11}$</td>
</tr>
<tr>
<td>Model II</td>
<td>6 mm</td>
<td>$5.78 \times 10^{-11}$</td>
</tr>
<tr>
<td>Model III</td>
<td>7 mm</td>
<td>$5.70 \times 10^{-11}$</td>
</tr>
</tbody>
</table>
Table 20. Calibration factor results for realistic skull model with changing thickness and asymmetry.

<table>
<thead>
<tr>
<th>Description of Model</th>
<th>Thickness Size (mm)</th>
<th>Calibration Factor ($\frac{\text{volts}}{\text{Pa}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model I</td>
<td>5 mm</td>
<td>$2.38 \times 10^{-06}$</td>
</tr>
<tr>
<td>Model II</td>
<td>6 mm</td>
<td>$2.30 \times 10^{-06}$</td>
</tr>
<tr>
<td>Model III</td>
<td>7 mm</td>
<td>$2.27 \times 10^{-06}$</td>
</tr>
</tbody>
</table>

![Graph showing calibration factor for different skull thickness sizes with constant 60 cm circumference.](image)

**Figure 93.** Calibration factor comparison between 5 cm, 6 cm, and 7 cm thicknesses.

5.5 COMSOL Modeling of Experimental PVC and 3D Printed Test Rig

The last finite element model is used to validate the calibration factor of volts per unit pressure of the piezoelectric PVDF sensor. The output of the piezoelectric PVDF wire sensor is a measured voltage, which is converted into charge using the custom charge amplifier gain associated with the wire. The charge amplifier gain used when testing the piezoelectric PVDF wire is $\frac{1000 \ pC}{10.12 \ \text{Volts}}$. The piezoelectric PVDF wire sensor also requires
a manufacturer sensitivity factor, which is estimated to be $3939393.9 \frac{pC}{strain}$. The last conversion factor is $\frac{strain}{pressure}$, which is the COMSOL output.

Combining both the experimental test data for the PVC test article with the finite element modeling data results in matching the PCB Piezotronic’s hydrophone pressure to the piezoelectric PVDF wire sensor pressure. Using the calibration factor shown in Figure 94, the hydrophone pressure matches the PVDF wire sensor pressure. The same calibration factor is also used for varying voltages displayed in Figure 95, which shows that the calibration factor is not dependent on the inside pressure.

**Figure 94.** Calibration factor for PVC test article.
Figure 95. Hydrophone pressure versus PVDF wire pressure on PVC test article. (a) Pump at 2V. (b) Pump at 6V. (c) Pump at 12V.

The next study involves the extruded 3D printed test articles. This study shows that the piezoelectric PVDF wire sensor integrates out all the asymmetries associated with the test articles. The calibration factor retrieved from COMSOL is shown in Figure 96.
This calibration factor is used for all 3D printed test articles. The experimental tests involve measuring the pressure for small asymmetry, medium asymmetry, and large asymmetry. The following figures shows the three different varying asymmetries tests at three different voltages.
Figure 97. Hydrophone pressure versus PVDF wire pressure on 3D printed test article. (a) Small asymmetry at 2V. (b) Medium asymmetry at 2V. (c) Large asymmetry at 2V.
Figure 98. Hydrophone pressure versus PVDF wire pressure on 3D printed test article.
(a) Small asymmetry at 3V. (b) Medium asymmetry at 3V. (c) Large asymmetry at 3V.
Figure 99. Hydrophone pressure versus PVDF wire pressure on 3D printed test article. (a) Small asymmetry at 5V. (b) Medium asymmetry at 5V. (c) Large asymmetry at 5V.

These results show that the piezoelectric PVDF wire sensor pressure correctly matches with PCB Piezotronic’s hydrophone pressure regardless of the asymmetry on the inside wall of the structure. The COMSOL model for the PVC test articles and the 3D printed test articles combined with the experimental data validates the preliminary assumptions because the same calibration factor of $\frac{\text{volts}}{\text{pressure}}$ is used regardless of interior asymmetries.
Chapter 6. Overall Discussion and Conclusion

This paper presents the use of a novel non-invasive piezoelectric PVDF wire sensor to measure intracranial pressure. The aim of this study is to determine whether a piezoelectric PVDF wire sensor is a viable option for measuring ICP. Other objectives were to validate a finite element model of a realistic skull and the piezoelectric PVDF wire sensor as well as obtain a calibration factor for the piezoelectric PVDF wire sensor for different size skulls. For the preliminary studies, the goal was to establish an understanding of the piezoelectric PVDF wire sensor and to prove that the asymmetries would indeed be integrated out by measuring the hoop strain. To verify this, simplistic 2D and 3D models were created within COMSOL, a multiphysics finite element modeling software, with varying size circumferences and asymmetries.

The next step was to obtain experimental data from Piezotronic’s hydrophone sensor and the piezoelectric PVDF wire sensor by building an experimental test rig. This data will then be used to validate the COMSOL model of a piezoelectric PVDF wire sensor. The test articles used were created from PVC piping and 3D printed technologies. Lastly, a realistic human skull model was used to obtain calibration factors for different size skulls. To create such a model, COMSOL is used to simulate the piezoelectric PVDF wire sensor being wrapped around a human skull. The model is then used to validate the measurement of the piezoelectric PVDF wire sensor to a known hydrophone pressure, obtain a calibration factor of $\frac{\text{volts}}{\text{pressure}}$, and to determine whether or not the piezoelectric PVDF wire sensor is affected by interior asymmetries.

The average percent error between the hydrophone and the piezoelectric PVDF wire sensor is 16.28%. The error could be due to external vibrations from the connections to the pump and the test article. Other suggestions of error could be from the sensor not being fully attached to the test article. Also, the rubber coating could have affected the damping and rigidity of the test article and not transfer all the strain into the sensor.

The COMSOL results for the preliminary and realistic models are as follows:

- For the preliminary 2D models and the 3D models, the percent difference in strain between the differences in asymmetries was 5.16% and 4.88% respectively.

- The calibration factors for the 53cm, 57cm, 60cm, and 62cm skull with a constant thickness of 6mm are the following: $1.78 \times 10^{-6} \frac{\text{volts}}{\text{Pa}}$, $1.94 \times 10^{-6} \frac{\text{volts}}{\text{Pa}}$, $2.30 \times 10^{-6} \frac{\text{volts}}{\text{Pa}}$, and $3.37 \times 10^{-6} \frac{\text{volts}}{\text{Pa}}$ respectively.

- The calibration factor results for the 60cm skull with changing circumference of 5mm, 6mm, and 7mm are the following: $2.38 \times 10^{-6} \frac{\text{volts}}{\text{Pa}}$, $2.30 \times 10^{-6} \frac{\text{volts}}{\text{Pa}}$, and $2.27 \times 10^{-6} \frac{\text{volts}}{\text{Pa}}$ respectively.
• Changing the thickness of the realistic model only produces a 4.68% change in variation.

• Changing the circumference while keeping the thickness constant produced a 47.15% change in variation.

These results show that the percent change in variation when changing the thickness, 4.68%, is relatively low when comparing to the percent change with respect to the varying circumference sizes, 47.15%. In Figure 100, the calibration factors for all the models including the models with varying thickness are overlaid on top of one another to show a visual representation of how changing the thickness and asymmetries on the inside are less likely to affect the calibration factor compared to when changing the skull circumference.

![Calibration Factor for Different Skull Circumference Sizes with Constant 6mm Thickness](image)

**Figure 100.** Comparison of all calibration factors for realistic skull model.

In conclusion, the novel non-invasive piezoelectric PVDF wire proves to be a successful sensor for measuring ICP. The results from the COMSOL finite element model proves that the piezoelectric PVDF wire sensor will in fact integrate out the thickness and asymmetries on the inside of the skull model. The piezoelectric PVDF wire sensor is dominantly affected by the different circumference sizes of the human head and will require a different calibration factor depending upon the circumference size of the
human. Thus the externally mounted piezoelectric PVDF wire sensor is able to measure absolute ICP, as well as measuring the change in ICP.

Chapter 7. Future Research

7.1 Additional Physical Experimental Testing

Some future research that could further expand the use of this non-invasive piezoelectric PVDF wire sensor involves the updating and expanding the depth of the experimental testing. An additional test includes recreating the 3D printed test articles with a non-porous material to avoid having to use a flexible rubber coating. Furthermore, increasing the vinyl tubing within experimental test rig may reduce vibrations from the water pump into the test articles. Other alternatives could include using an underwater piezoelectric actuator inside a fully enclosed test article as the pulsation source to reduce components of the experimental test rig.

Other future experimental testing includes comparing the piezoelectric PVDF wire sensor measurements with in field measurements at hospitals through use of patients already undergoing EVD. These experimental tests enable a direct comparison of the measured pressure from the piezoelectric PVDF wire sensor to the measured intracranial pressures from EVD.

7.2 Additional Finite Element Modeling

To further elaborate on the finite element model, human skull geometry can be directly created from the use of MRI scans. This will give the finite element results an even more realistic solution as opposed to the just having realistic circumferences and thicknesses of the skull. Furthermore, the elements of the piezoelectric PVDF wire sensor can be broken down into individual sections and model each wire layer individually to ensure exact material properties.

7.3 Enhancement of Piezoelectric PVDF Wire Sensor

The piezoelectric PVDF wire sensor could be configured to allow for wireless data transmission. This would allow for convenient data acquisition and less cable interference. Also, developing a system or device to appropriately attach the piezoelectric PVDF wire to the human skull would be very beneficial. The development of this system would help eliminate any operator error that may exist and may also apply a better fixed boundary condition to the skull.
7.4 Experimental Testing on Hospital Patients

Lastly, because the piezoelectric PVDF wire sensor is a viable option for measuring ICP, testing on patients in hospitals would enable the sensor to be compared directly to current invasive ICP measuring techniques such as external ventricular drainage.
References


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Appendix A: Fundamental Hoop Strain Theory

This appendix provides fundamental equations associated with solving hoop strain for a cylinder from [50]. The hoop strain is dependent upon the hoop stress and axial stress shown in

\[
\sigma_H = \frac{pd}{2t} \quad (34)
\]

\[
\sigma_L = \frac{pd}{4t} \quad (35)
\]

where \( p \) is the interior pressure, \( d \) is the interior diameter, and \( t \) is the thickness. Substituting the hoop stress and the axial stress in the hoop strain equation yields,

\[
\epsilon_H = \frac{1}{E} \left[ \sigma_H - \nu \sigma_L \right] \quad (36)
\]

\[
\epsilon_H = \frac{1}{E} \left[ \frac{pd}{2t} - \nu \frac{pd}{24} \right] \quad (37)
\]

where \( E \) is Young's Modulus and \( \nu \) is poison's ratio. Doing a quick analysis with arbitrary values will yield similar results to those in 3.1.2 Results of 2D Preliminary Finite Element Analysis.