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Non-Invasive Early Detection of Brain Aneurysm Symptoms by Fiber Bragg Grating Sensors

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Abstract: Brain Aneurysms are a critical cerebrovascular condition where there is bulging of the arterial blood vessels, with the rupture adding to the mortality rates up to 50%. Early detection remains challenging as traditional diagnostic methods, such as MRI and CT Angiography, are invasive, expensive, and often inaccessible for the earliest screening. This study presents a novel approach using Fiber Bragg Grating (FBG) Optical sensor technology for the non–invasive, earliest detection of Brain Aneurysms identified via analysis of arterial pulse waveforms. The proposed system utilizes an FBG sensor fabricated using the phase mask technique and is mechanically placed in the temple region to detect subtle changes in pulse wave characteristics, which could potentially indicate a Brain aneurysm. The FBG sensor-based approach offers numerous advantages over conventional methods, such as immunity to electromagnetic interference, high bandwidth and strain sensitivity, light weight, compactness, low security risk, and the capability for continuous real-time monitoring. Initial results provide the system's ability to detect minute pulse wave variations, which may indicate the unruptured aneurysms, potentially enabling earlier detection through a non-invasive and optical fiber technology-based approach.
Keywords: Optical Fiber Sensors, Fiber Bragg Grating, Fiber Interrogator, Temporal arterial pulse, Brain Aneurysm, Non-invasive detection, Intracranial pressure, pulse waveform analysis.

I. INTRODUCTION

In recent years, the integration of sensor technologies with the healthcare domain has created opportunities for innovation, with the FBG sensors emerging as one of the innovative methods in non-invasive pulse monitoring. This paper focuses on the design and application of the FBG sensors for the temporal arterial pulse wave analysis. The continuous real-time monitoring of pressure and strain measurements of the temporal arterial pulse provides more accurate and highly sensitive health status statistics compared to conventional methods [1]. Brain aneurysms, primarily the intracranial aneurysm (IA), are characterized by the bulging of blood vessels resulting from a weakened region within the cerebral artery wall in the brain. An aneurysm depicts the weakened area within the arterial blood vessel that will bulge, thereby disrupting the normal blood flow and leading to a potential hemorrhagic stroke. Many patients with subarachnoid hemorrhage present with severe headache. In the human vascular system, blood flow is classified as either laminar, which is the smooth, straight, and orderly flow of blood, or turbulent, which is the smaller, irregular, and curved blood vessels. Brain aneurysms can be caused by the turbulent flow conditions, in which the blood velocity increases, thereby increasing the geometric complexity of the blood vessels, which in turn exerts the mechanical stress on the vessel wall. The continuous abnormal blood flow can thereby disrupt the endothelial cell function, which is an important factor in the development of the IA [2]. Smoking, alcohol consumption, hypertension, genetic disorders, and other factors can be considered significant factors of risk factors for the development of the IA [2]. The conventional methods of detection include MRI, CT Angiography (CTA), Digital Subtraction Angiography (DSA), MRA, etc., but these are expensive, invasive, require ionizing radiation, and risky for claustrophobic high-risk patients. The traditional methods are the neurosurgical methods for the cure of Brain aneurysms are microsurgical clipping, Endovascular coiling, or flow diversion with stents, but there is a high risk associated with all these procedures. [2]. In recent studies, it has been reported that incidental unruptured aneurysms are more notable in females compared to males. Long-term studies indicate that females are at a higher risk of developing de novo aneurysms, and they have been identified as an independent risk factor for the growth of unruptured cerebral aneurysms. Another study analyzing unruptured aneurysms concluded that female sex was a significant risk factor for aneurysm growth.

II. RELATED WORK

Many researchers have proposed different solutions for the detection of brain aneurysms, which are currently in use in the medical field. They are mainly the imaging techniques and tools, such as Magnetic resonance imaging (MRI) is highly effective for the visualization of tissue structures, but this is not suitable for some patients who have pacemakers, metal implants, or claustrophobic conditions.

Computed tomography angiography (CTA) can be an option for the initial diagnosis of the ruptured aneurysm, and Magnetic resonance angiography (MRA) for the later stages of detection. Lately, digital subtraction angiography (DSA) can be used as the golden standard for detection; however, it is not cost-effective. Generally, they use the combination of CTA and DSA for the imaging, where they get the detailed visuals of the blood flow patterns and the aneurysm characteristics.

The newly developed 3D navigation systems have benefits during aneurysm surgery as its minimally invasive and cause minimal cortial damage. Some non-invasive methods were also used, such as CTA, but it is less effective in detecting aneurysms near the skull bone location, and DSA is an invasive procedure and carries risks like neurological complications and severe allergic reactions as well.

A three-dimensional catheter angiography was also developed in 1998 that permitted the reformatted images to be rotated. However, this, with or without the advanced three-dimensional capability, is very invasive and expensive and has risks, as experienced operators are much less compared to those of other techniques. Non-neurologic risks such as femoral artery injury, groin hematoma, and adverse renal effects and allergies also contribute. Angiographic examination almost fails to disclose 10 to 20 percent of cases of the subarachnoid haemorrhage. Researchers have also discovered that the acute effects of the subarachnoid hemorrhage, which is the hydrocephalus that develops in about 20 percent of the aneurysmal subarachnoid hemorrhage patients. Cerebral vasospasm is also a major cause of mortality. There are certain newer devices that are being utilized for the treatment of brain aneurysms, other than the clipping and coiling surgical methods, such as flow disruption devices, pCONus, Endovascular clip system, pulse rider, and several other devices are currently in the stages of development, and trials are going on. The disadvantages that are seen in the existing technologies, such as non-invasive, patient-friendly, etc.

This review of the existing literature and the technologies clearly states the need for a dedicated, easily accessible, and non-invasive device. Our proposed device can contradict.

III. PROPOSED METHOD

A. *Overview of Proposed Method*

FBG Sensors are one of the best wavelength-selective fiber sensors. They exhibit high sensitivity to the slightest changes in mechanical strain, making them ideal for capturing even the subtle variations in the temporal arterial pulse. The sensitivity here refers to even detecting the slightest variations in the waveform with more accuracy than conventional methods. The advantage of FBG sensors to withstand even the harsh environmental conditions makes them an easy approach for long-term, continuous, real-time monitoring. FBG sensors address the problem of using surgical techniques with a non-invasive approach. It is placed in the temple region of the head as the skull is a little thinner in that region; these offer patients' comfort while continuously monitoring the subtle variations. Fiber Bragg Grating is based on the principle of Fresnel reflection.[1] Bragg wavelength is the fundamental principle used for the reflection of light from the mechanical structure of FBG. It is given by the equation as follows:

$n\lambda = 2 \wedge \sin (\theta$ (1)

Where n is the order of reflection, λ is the wavelength of incident light, and angle of incidence θ. Bragg wavelength is the wavelength of light that obeys the Bragg condition for reflection and is given by:

$\lambda_B = 2\, n_{eff} \wedge$ (2)

Where n_{eff} is the effective refractive index of the core in the optical fiber cable, and $\wedge$ is the grating period.[2]

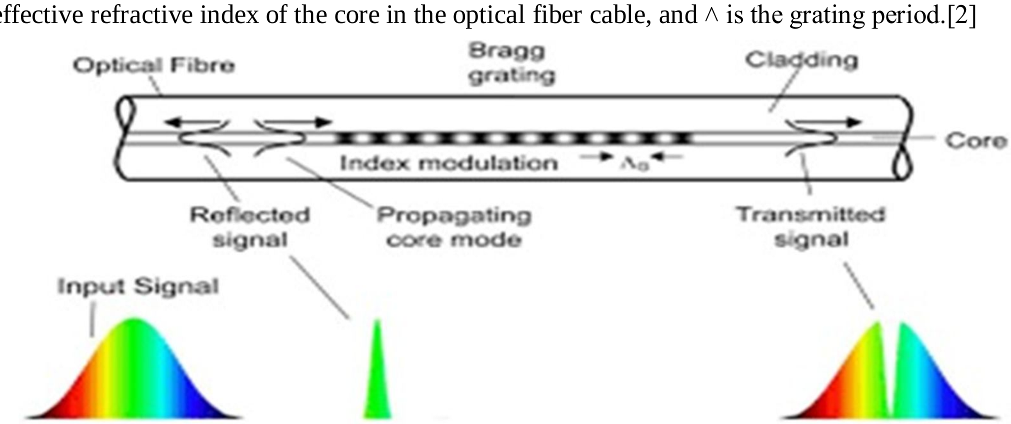

Figure 1. Fiber Bragg Sensor working

The flowchart of the proposed headband device for the detection of brain aneurysms is shown in Figure 2.

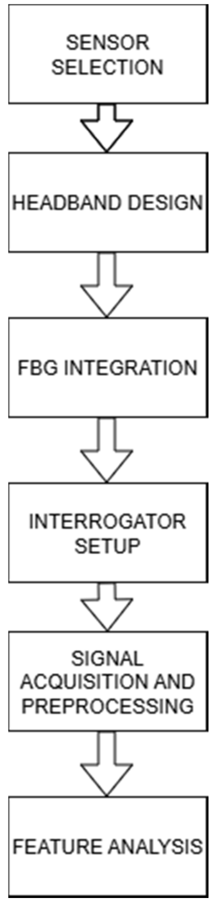

Figure 2. Flowchart of the proposed headband device

The flowchart describes the stages of the procedure carried out for the detection of an aneurysm:

Step 1. Sensor selection:

Identify critical parameters (strain, pulse waveform, pressure) and select suitable sensors. In our proposed device, we have selected the Fiber Bragg Grating (FBG) Sensor.

Step 2. Headband design:

A lightweight, flexible headband made of medical-grade polymer or soft elastomer. Sensors are embedded at strategic points along the temple, where the superficial temporal artery lies close to the skin.

Step 3. FBG sensor Integration:

The FBG sensors are connected via optical fiber to an optical interrogator. The interrogator tracks real-time wavelength shifts ($\Delta\lambda B$), which correspond to changes in strain/pressure.

Step 4: Signal acquisition and preprocessing:

Optical signals from the interrogator are converted to a digital format via a USB/serial interface to a PC/laptop. Noise filtering and conversion of wavelength shifts into physical units like strain ($\mu\varepsilon$) or pressure (mmHg).

Step 5. Feature Extraction:

Visualisation tools like OriginPro are used for the OriginPro for signal plotting, pulse shape analysis, and the extracted features are such as Pulse amplitude, rise/fall time, dicrotic notch detection, strain variation trends indicating changes in compliance, and anomalous waveform signatures suggestive of aneurysmal progression.

Using simulation and synthetic data generation, we test the system's performance using simulated waveforms that mimic both normal and aneurysm-prone signals.

B. Methodology:

The block diagram properly explains the methodology for the data acquisition and analysis from the FBG sensor, as shown in Figure 3:

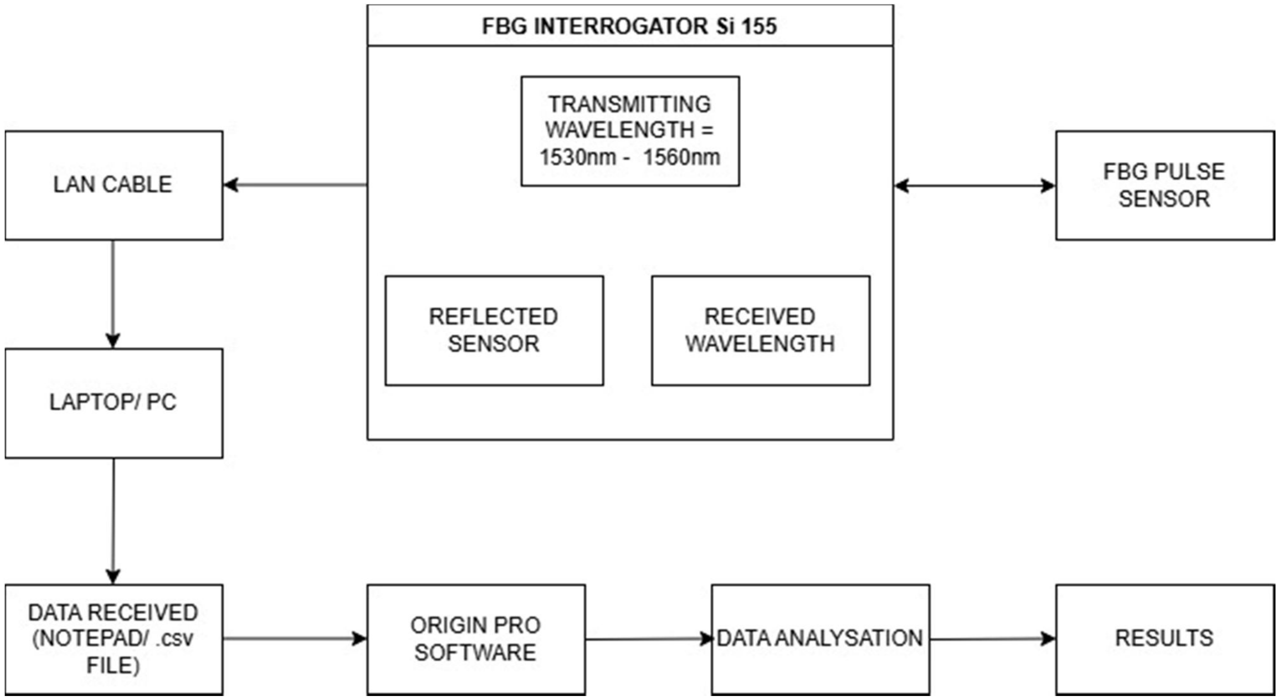

Figure 3. Block diagram of the proposed headband design for the detection of a Brain aneurysm

The synthetic data was simulated under various conditions, incorporating factors such as vessel strain, intracranial pressure, and pulse wave velocity. The simulation was made for the generation of realistic data reflective of changes in the pulse wave characteristics during the early stages of aneurysm formation. Two data sets were generated for normal waveform with high amplitude waveform ~ 1.2 Hz, and aneurysm-prone prone are flattened low frequency signals ~0.9 Hz. The Pulse wave velocity, rise time, mean pressure, vessel wall strain, and intracranial pressure (ICP) reference readings are taken from. We have used the Savitsky–Golay filter for smoothing the noisy signals without changing peaks, width, and height. We then extracted signal skewness and kurtosis, strain amplitude, and simulated pulse wave velocity from peak time variations.

The main sensing element is an optical fiber sensor embedded with a Bragg grating, and an optical-based medium is used, which is fabricated using the phase mask technique that creates the periodic refractive index modulations in the core of the optical Fiber. The FBG is developed with a Bragg wavelength between 1530 nm – 1560 nm of the C-band for the optical compatibility with the interrogator system. The created FBG sensor is bonded to this mechanical structure using an adhesive to ensure maximum strain sensitivity for the system.

The FBG sensor assembly will be positioned and placed over the temporal artery region, where the skull is thinner, and the subtle changes of strain and pressure can also be detected by the sensor. An Si–155 FBG interrogator is used as both the light source and detection system as well and it transmits the light to the FBG sensor and also analyses the reflected wavelength spectral signatures. The interrogator also converts the received FBG sensor data into readable digital signals. The wavelength shifts in the reflected spectrum will correspond directly to the strain and pressure variations caused by the arterial pulsations by the sensor. A digital stethoscope is used as a reference for calibration, allowing the relationship between pulse measurements and sensor readings. The FBG interrogator is then connected to the laptop or PC via a LAN cable for real-time data acquisition. Enlight software was used to capture and record the wavelength shift data. Data was collected at a sampling rate of 1 kHz to ensure the standard temporal resolution of the pulse waveforms. All the readings were saved in a CSV file format for the next sub-processing and analysis. The raw wavelength shift data were imported into the Origin Pro software for real-time analysis. Signal processing techniques, including normalization, filtering, smoothing, and peak detection, were applied to separate the pulse waveform components. Statistical analysis was performed to distinguish the differences between the normal and pathological aneurysm waveforms.

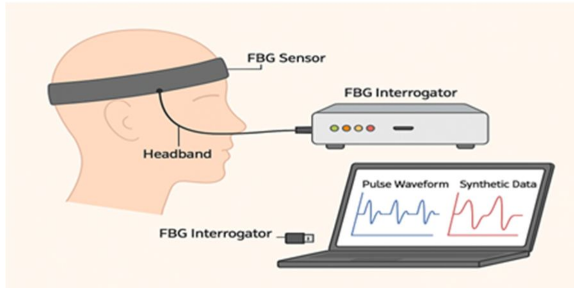

Figure 4. Experimental Setup

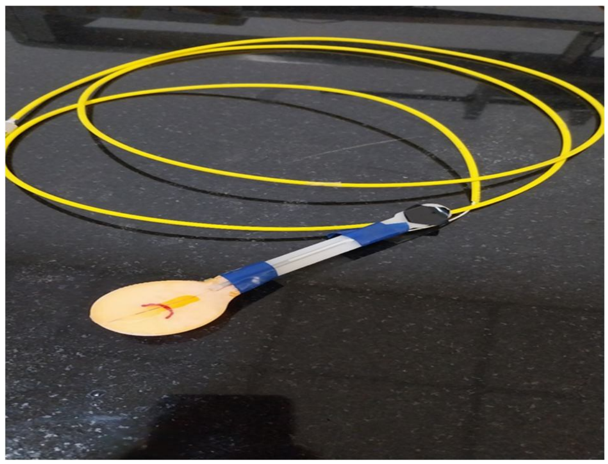

Figure 5. FBG sensor used

IV. RESULTS AND DISCUSSION

The following graphs are the results obtained from our proposed headband for the detection of the brain aneurysm:

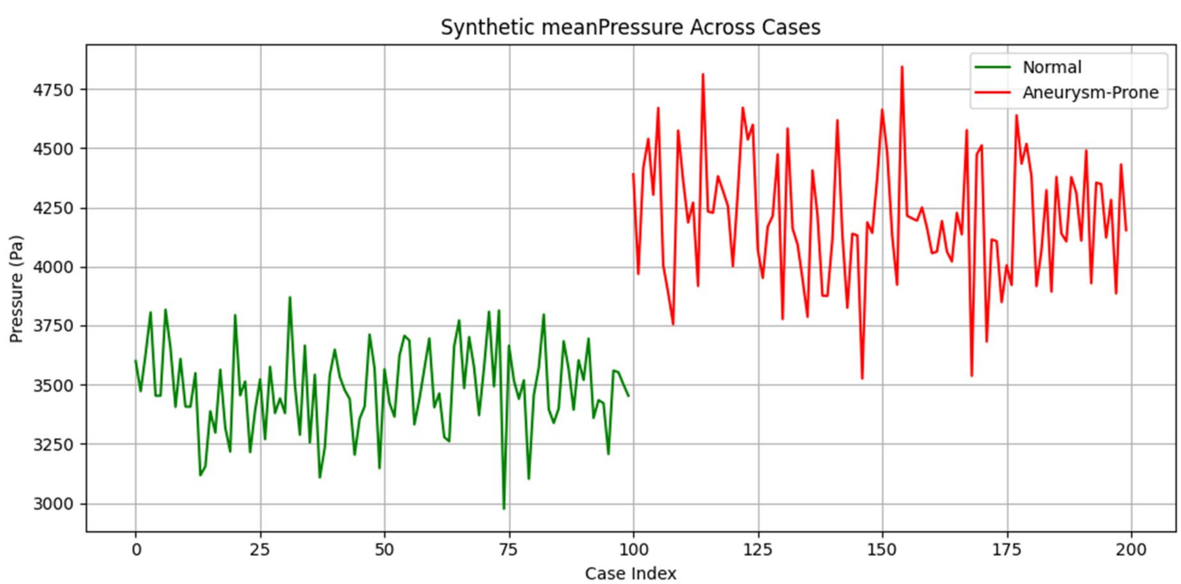

Figure 6 . Synthetic Data Generated graph

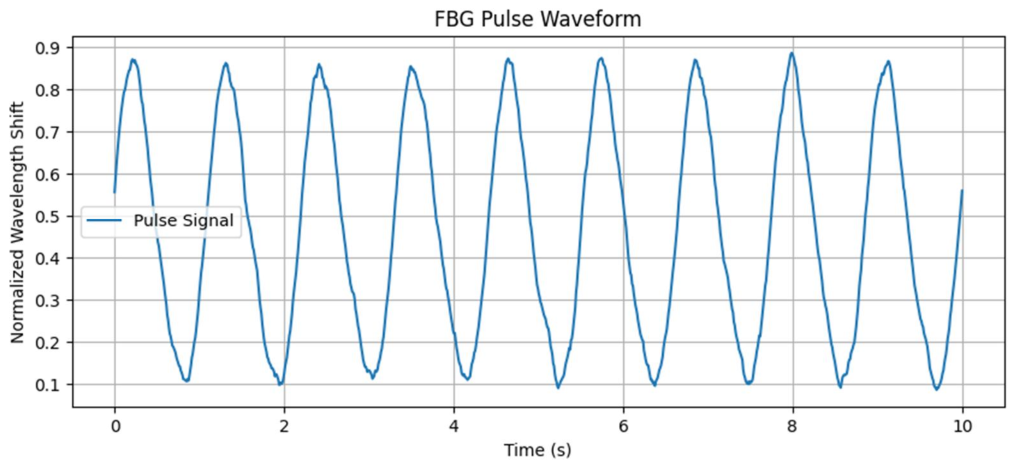

Figure 7. Normal condition Graph obtained for the values

The classification used here for the detection and difference between normal and aneurysm-prone waveforms is that: The normal waveform is high kurtosis, low skewness, fast rise time, and high amplitude, and the aneurysm-prone prone is flattened, low amplitude, and low-rise time.

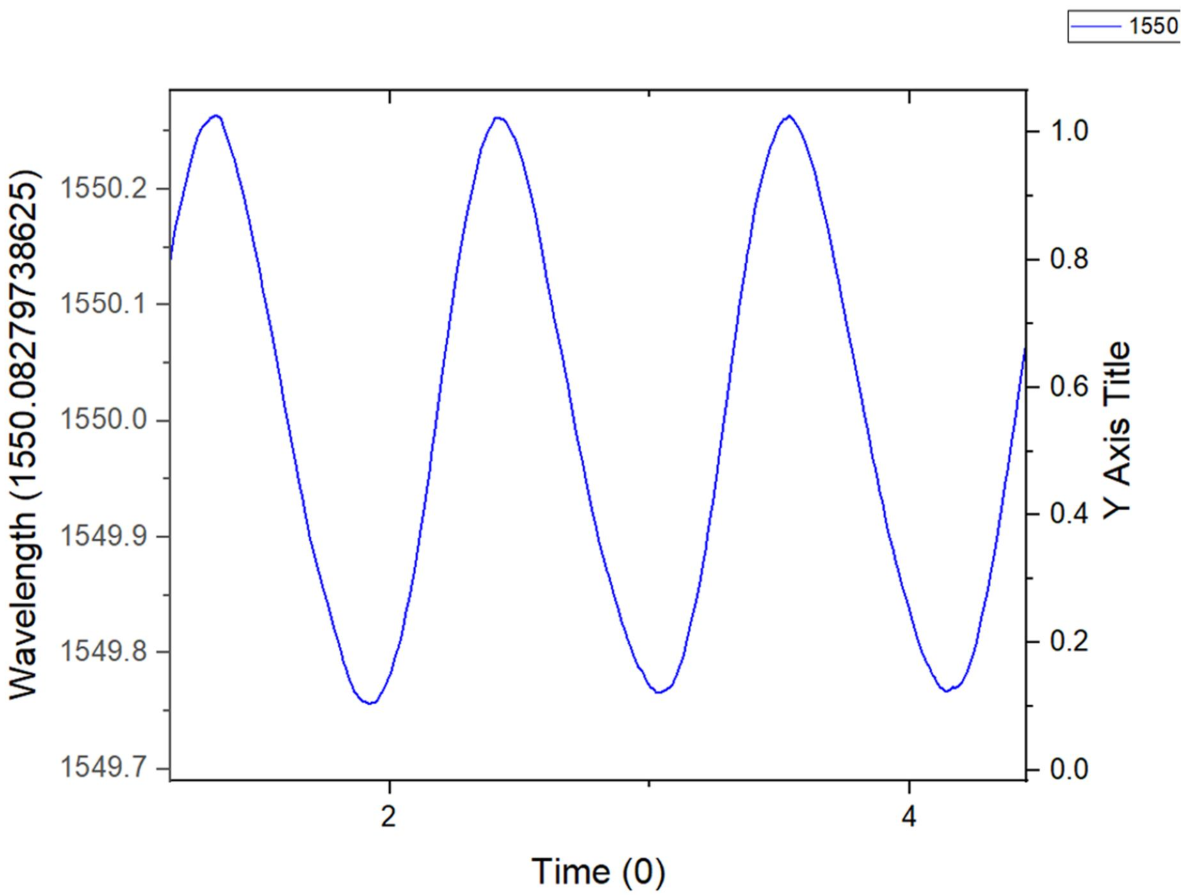

Figure 8. Aneurysm-prone graph

Parameter	Normal value	Aneurysm prone
Pulse Frequency (Hz)	~1.2	~0.9
Rise time (s)	~0.2	>0.45
ICP (mmHg)	~10	~20
Mean pressure (Pa)	~3500	~4200
Pulse wall velocity (m/s)	~5.5	~8.0
Wall strain	~0.6	~0.3
Skewness	~0.5	~1.4
Kurtosis	~2.0	~1.2

Table I. Values for detection from the reference

Elevated peak 2 than peak 1 indicates the higher intracranial pressure and the flattening of the waveform due to the vessel wall strain. The normal waveforms are moderately skewed to the right, and in aneurysm-prone prone are highly skewed, which indicates a delayed pressure rise as a significant sign of the vessel wall compliance issues or abnormal blood flow. Normal waveform has moderate kurtosis, which is an indication of the healthy peak sharpness, and aneurysm-prone prone are flatter and broader, which is a sign of elasticity loss in vessel walls and the vascular damping. Strain amplitude determines the degree of vessel wall that is deformed in a pulse, and in aneurysm aneurysm-prone graph, the strain is reduced, which indicates the walls are stiff and bulging.

V. CONCLUSION

This study shows that the FBG sensors, when integrated in the headband configuration, which is non-invasive, can detect the physiological parameters relevant to the brain aneurysm symptoms. The simulated waveforms and the analysis of results obtained show that there is a change in the waveform features, such as rise time, strain amplitude, and waveform asymmetry describe the differentiation between normal and aneurysm-prone conditions Through the strategic placement of FBG sensors over the superficial temporal artery, the system can capture critical physiological parameters such as pulse waveform morphology, cranial strain, and vascular compliance. The use of optical sensing makes the system immune to electromagnetic interference, lightweight, and suitable for integration into wearable devices like a headband. The combination of Python and OriginPro allows for real-time data logging, visualization, and signal analysis, making the system adaptable for both research and future clinical environments.

By generating and analysing synthetic physiological waveforms, the system's capacity to detect abnormal patterns associated with aneurysmal conditions was validated at the simulation level. Although clinical testing has not yet been performed, the system offers a proof-of-concept that non-invasive FBG-based monitoring could serve as an early-warning tool for high-risk individuals. The proposal also illustrates the feasibility of developing scalable, modular, and real-time monitoring tools that align with current trends in smart healthcare and personalized diagnostics.

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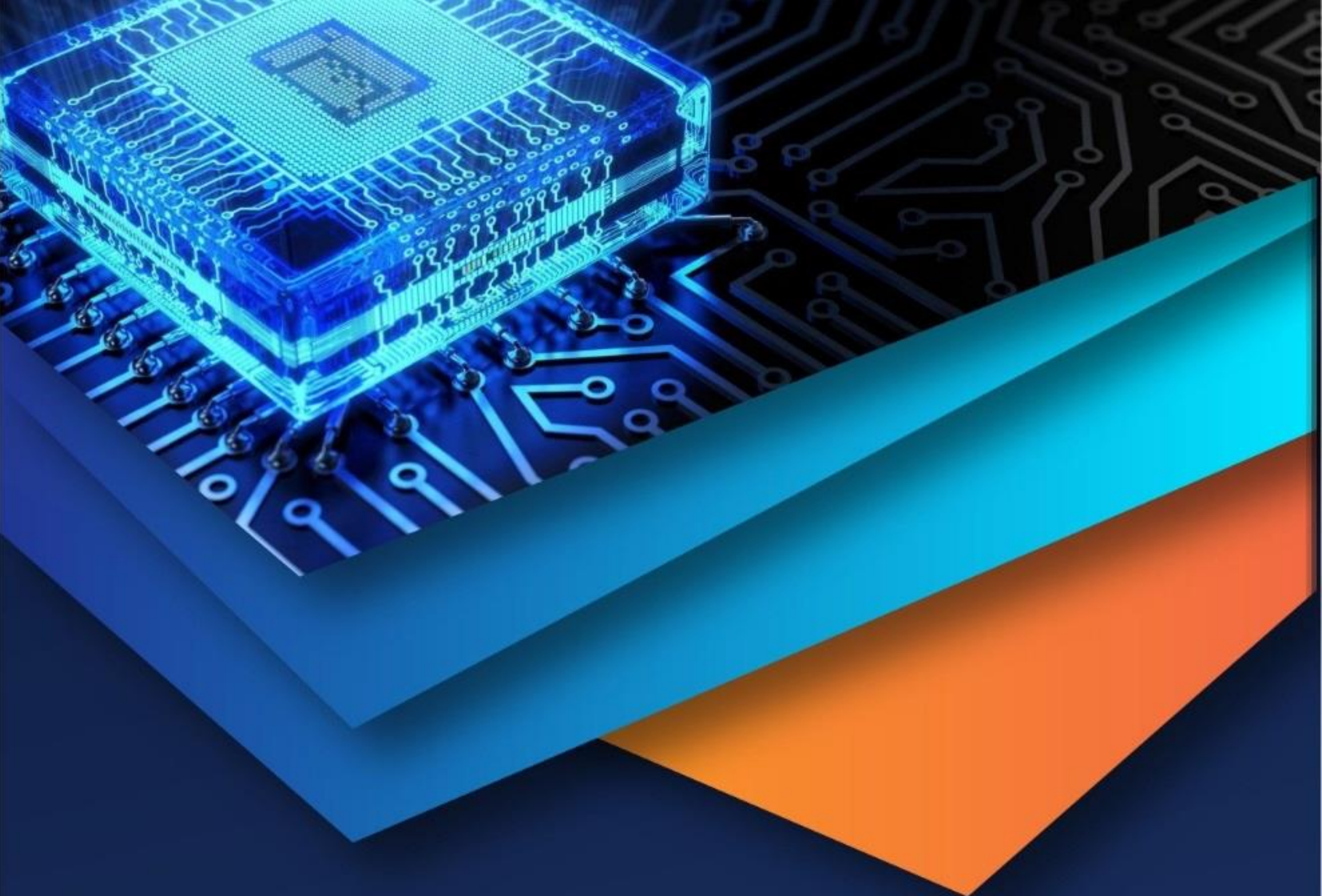

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