

Development of an Alternative Technology for Blood Vessel Blockage Detection Using Photo Acoustic Imaging

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Abstract - The financial and accessibility limitations of conventional vascular imaging methods are significant, especially in under-resourced areas. To mitigate this, we introduce a cost-effective photo acoustic imaging (PAI) system for identifying simulated occlusions in artificial blood vessels. Capitalizing on photo acoustic imaging's strong optical absorption contrast and non-ionizing nature, our system employs a 650nm laser diode to induce sound waves within a custom phantom mimicking blocked vasculature. A piezoelectric sensor detects the resulting ultrasound, which is digitized via an Arduino Uno and processed in MATLAB. Blockages are visualized through an interpolated map of maximum (or average) signal strength across measurement locations. Our findings demonstrate the viability of this affordable technique for visualizing vascular structures and detecting obstructions in low-resource contexts and as an educational tool. This study establishes a foundation for future enhancements in system performance and the integration of more sophisticated imaging algorithms.

Keywords – Photo acoustic Imaging (PAI); Vascular Blockage Detection; Simulated Vessels; Phantom; Vascular Visualization; Optical Contrast; Non-ionizing Radiation

I. INTRODUCTION

The human body depends on its circulatory system which consists of a vast network that includes arteries veins and capillaries to maintain constant oxygen and nutrient delivery to every cell while eliminating waste created through metabolism. The world faces a significant health problem due to blockages that occur in these essential blood vessels which medical professionals refer to as vascular blockages or occlusions. The blockages which happen because of thrombi (blood clots) and emboli (migrating masses) and the slow process of atherosclerosis (stenosis) that narrows blood vessel openings will lead to either partial or total suspension of blood circulation to body parts.

The consequences of such vascular impairment are widespread, manifesting in a range of debilitating and often fatal conditions which include myocardial infarction (heart attack) and ischemic stroke and pulmonary embolism and peripheral artery disease. The world experiences major health problems because vascular diseases affect a large number of people and have serious medical effects. Thrombotic and atherosclerotic events that cause blockages, which lead to cardiovascular diseases, represent the main reason for death worldwide. The World Health Organization (WHO) reports that in 2019 cardiovascular diseases (CVDs) caused approximately 17.9 million deaths which constituted 32% of global mortality and 85% of these fatalities resulted from heart attacks or strokes. [1] The World Heart Federation (WHF) reported that deaths from cardiovascular disease (CVD) jumped globally from 12.1 million in 1990 to 20.5

million in 2021. [2] In India, the burden of cardiovascular diseases has been progressively increasing. In 2016, out of the 17.9 million deaths in the world that occurred due to CVDs, India accounted for 27% of them. [3-4] The economic and societal costs associated with the management and treatment of these conditions are considerable, emphasizing the crucial need for effective diagnostic and monitoring tools.

Accurate and prompt detection of vascular blockages is of paramount importance for guiding appropriate clinical interventions, encompassing thrombolytic therapy, angioplasty, and surgical bypass procedures. Current clinical imaging modalities employed for this purpose include Doppler ultrasound, computed tomography angiography (CTA), magnetic resonance angiography (MRA), and conventional contrast-enhanced angiography. While each of these techniques offers unique advantages, they also present inherent limitations, such as limited sensitivity (Doppler ultrasound), exposure to ionizing radiation and risks associated with contrast agents (CTA, conventional angiography), and high cost with lower temporal resolution (MRA).

In response to the need for enhanced vascular imaging techniques, photo acoustic imaging (PAI) has emerged as a promising and rapidly evolving modality. [5] By leveraging the photo acoustic effect – the generation of ultrasound waves upon the absorption of pulsed light – PAI provides a distinctive combination of high optical absorption contrast and scalable ultrasound resolution. Hemoglobin functions as the main chromophore in blood which shows strong optical absorption throughout both the visible spectrum and the near infrared spectral range. This property creates a natural contrast method which scientists use to achieve precise blood vessel detection without needing additional contrast materials. The signal's acoustic properties allow it to penetrate tissue more effectively than traditional optical techniques which helps to reduce the diagnostic limitations that optical coherence tomography and microscopy face during vascular imaging.

The implementation of PAI technology in commercial systems faces major hurdles because these systems require advanced technical expertise and their operation needs expensive funding. The development of this technology remains blocked because it needs special resources and educational environments to test its capabilities. Our research project will create and test a budget-friendly photo acoustic imaging system by using components which are both easy to find and economical. The system uses a 650nm laser diode together with an economical piezoelectric sensor for ultrasound detection and an Arduino Uno microcontroller platform which controls the laser and records data. The primary goal of this study is to demonstrate the feasibility of this simplified PAI approach for the detection of simulated vascular blockages within a custom-designed phantom that mimics the optical and acoustic properties of biological tissues and the presence of occlusions.

We will demonstrate how this affordable technology enables basic

vascular imaging through our examination of photo acoustic signals and our creation of spatial acoustic amplitude maps. The research findings establish a starting point for testing low-cost PAI systems which could be utilized in vascular assessment and educational purposes while serving as a bridge to advanced clinical PAI systems.

II. LITERATURE REVIEW

The specialized features of Photo acoustic Imaging (PAI) which include its ability to produce high optical contrast together with its capacity to deliver precise spatial details and its deep tissue imaging capabilities and its functional imaging methods, make it a highly promising research instrument which medical practitioners can use to investigate various biological processes and medical conditions.

Manojit Pramanik et al.[6] explored combining photo acoustic (PA) and ultrasound (US) imaging has been explored to harness PAI's high optical contrast and US's structural information. A handheld probe demonstrated in vivo human finger joint imaging, visualizing both skin/bone structure and blood vessels. This multimodal approach offers complementary data, potentially aiding disease diagnosis by integrating mechanical and optical tissue properties. However, the study mainly showed the feasibility of the combined system and didn't deeply explore specific PA/US technology limitations beyond general challenges of 2 each modality (e.g., US penetration, PAI contrast agents).

Kayo Yoshimoto et al.[7] developed a portable photo acoustic and ultrasound imaging system, utilizing an LED light source, was created for skin condition monitoring. In vivo testing on a human heel with a wound showcased the system's capability to image both blood distribution (via photo acoustics) and tissue structure (via ultrasound). This research tackled a significant drawback of traditional photo acoustic systems—their bulkiness and expense stemming from the reliance on solid-state lasers.

Xiaoqing Wang et al.[8] came out with a movable photo acoustic and ultrasound imaging system, exercising an LED light source, was created for skin condition monitoring. In vivo testing on a mortal heel with a crack showcased the system's capability to image both blood distribution (via photo acoustics) and tissue structure (via ultrasound). This exploration dived a significant debit of traditional photo acoustic systems their luminousness and expenditure stemming from the reliance on solid- state spotlights.

Zhihao Zuo et al.[9] proposed a novel simulation framework using position-based dynamics to model catheter/guidewire movement and contrast agent dispersion, designed for speed and stability. The simulation incorporates a bounding volume hierarchy (BVH) for efficient collision detection and Coulomb's law for contact response. The authors cite the difficulty of achieving stable catheterization simulation with previous elastic force-driven models as motivation, but a disadvantage of this work is that it relies on accurate vessel centreline extraction, which can be challenging in complex anatomies.

Ge Zhang et al.[10] explored the use of low-boiling point phase-change nanodroplets, derived from existing commercial ultrasound contrast agents, for in vivo photo acoustic imaging. Experiments on mice showed enhanced signals in the spleen and intestines after droplet activation, indicating their potential as photo acoustic contrast agents. However, the mechanism of photo-activation in the nanodroplets, which lack a dye coating, is identified as a potential area needing further study.

Tao Chen et al.[11] introduced a new photo acoustic imaging instrument with a semi-ring transducer array, intended for improved imaging of human peripheral vasculature. The system provided high-resolution, deep penetration imaging, and enabled rapid volumetric

data acquisition from limbs. The authors highlight its advantages over existing methods, including a larger field of view and better portability. However, the manuscript does not extensively discuss any specific disadvantages or trade-offs associated with the new system design.

Tri Vu et al., [12] examined the significance of low- frequency signals in photo acoustic computed tomography (PACT), challenging the common practice of fastening solely on high- frequency signals. The exploration indicates that low- frequency signals contribute to structural visibility, quantitative delicacy, and reduced vestiges in PACT imaging. The paper identifies the limited discovery bandwidth of ultrasound transducers and their treatment as background noise as a disadvantage in PACT.

III. METHODOLOGY

The Fig. 1 illustrates the fundamental steps involved in a photo acoustic imaging (PAI) system designed to detect blockages within a blood vessel phantom. This technique combines the advantages of optical and ultrasound imaging to provide enhanced visualization.

This study presents a custom-built photo acoustic imaging (PAI) system designed to detect and visualize simulated vascular blockages within a tissue-mimicking phantom. Central to the system's operation is an Arduino Uno microcontroller [15] , which manages both the precise timing of the laser pulses and the acquisition of acoustic signals from a piezoelectric sensor. In this setup, the laser diode [13] is wired to digital pin 9 on the Arduino, enabling the microcontroller to deliver well-timed electrical pulses that control the emission of light. Meanwhile, the piezoelectric sensor [14], which is responsible for detecting the acoustic waves generated during the photo acoustic effect, is connected to analog pin A0. This arrangement 3 allows the Arduino to read analog voltage signals produced by the sensor when it detects pressure changes resulting from the absorption of laser pulses within the phantom.

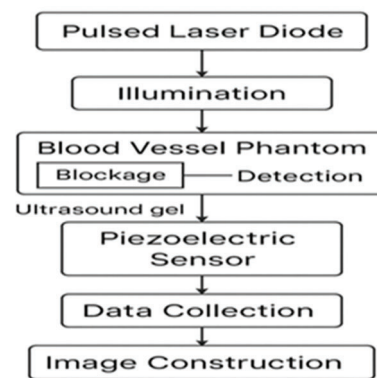


Fig.1: Proposed model of a Photo acoustic System for Detecting Blood Vessel Blockage

The operation begins with the Arduino triggering the laser diode to emit brief, controlled bursts of light at a wavelength chosen to maximize absorption by the materials inside the phantom—particularly the regions meant to simulate blood vessels and blockages. When the laser light is absorbed by these materials, it causes a rapid temperature increase, leading to swift thermal expansion. This expansion generates acoustic waves, the intensity of which is directly related to the amount of light absorbed. As a result, areas within the phantom that absorb more light—such as those representing a blockage - produce stronger acoustic signals than less absorptive regions.

To create a realistic blockage within the phantom, a mixture of ultrasound gel and black ink is injected into the vessel-like structure.

The presence of ink increases the optical absorption of the gel, making the simulated blockage more responsive to the laser pulses. This mimics the behaviour of actual blood clots, which have different optical properties compared to the surrounding tissue, and therefore generate stronger photoacoustic signals. The CAD model of the tubular phantom is shown in Fig. 2. The fabricated phantom with two angled branches is illustrated in Fig. 3. The final 3D printed phantom used for experimentation is shown in Fig. 4.

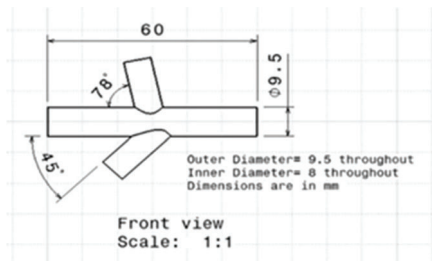


Fig.2: CAD model of tubular phantom (vascular mimicking)

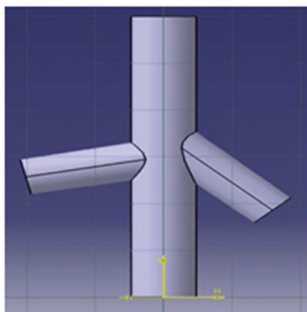


Fig.3: Front View of a Tubular Phantom with Two Angled Branches



Fig.4: 3D Printed Phantom (blood vessel)

The piezoelectric sensor detects acoustic signals which it converts to electrical voltages through its connection to the phantom and its use of ultrasound gel for acoustic wave transmission. The Arduino system digitizes analog signals which it receives from pin A0 and then transmits the data to a computer for analysis. The collected signals undergo processing through a moving average filter which reduces noise before the signals are interpolated onto a finer grid to create a two dimensional map of photo acoustic signal amplitudes. The map displays the optical absorption distribution throughout the phantom while it shows the simulated blockage as a prominent feature.

The laser diode connection with digital pin 9 together with the piezoelectric sensor connection to analog pin A0 enables the photo acoustic imaging system to succeed as a vascular blockage detection method. The system generates high-contrast images through its ability to detect variations in optical absorption which demonstrates PAI's potential for use in non-destructive medical imaging.

IV. RESULTS

This study utilized photo acoustic imaging for detecting a simulated vascular blockage, and the results are depicted in three figures.

Fig. 5 illustrates the raw piezoelectric sensor signal response, showing the amplitude of the signal (in ADC units) as a function of the pulse number, which corresponds to different scan positions. Fig. 6 presents a comparison of the raw and processed signals, highlighting the effect of the moving average filter on noise reduction. Finally, Fig. 7 displays the interpolated photo acoustic amplitude map, a visual representation of the spatial distribution of the photo acoustic signal amplitudes.

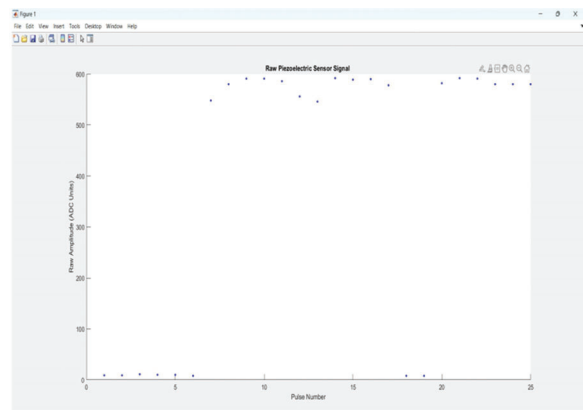


Fig.5: Raw Piezoelectric Sensor Signal Response

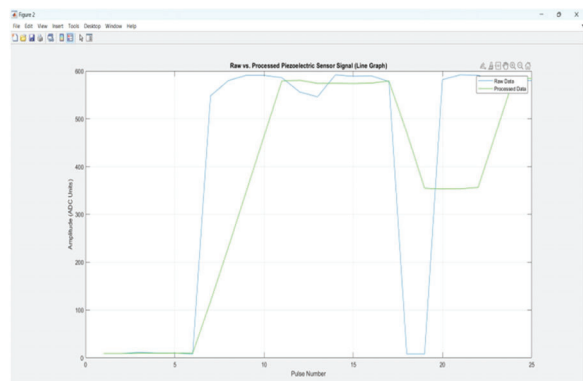


Fig.6: Comparison of Raw and Processed Piezoelectric Sensor Signals

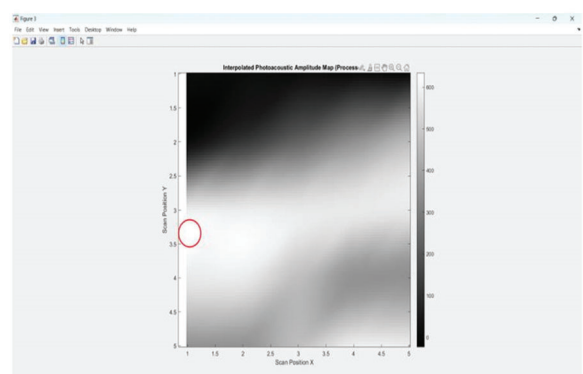


Fig.7: Interpolated Photo acoustic Amplitude Map

The results demonstrate successful detection and successful localization of the simulated vascular blockage. In Fig 5, the raw signal amplitude shows a distinct peak around pulse number 10 which indicates a strong photo acoustic response at that particular scan position. The peak indicates the blockage location because higher

optical absorption results in greater acoustic signal production. Fig 7 shows the spatial distribution of the signal which includes a visible area of high intensity. The region marked with red circles represents the localized area of increased optical absorption and it confirms the precise blockage location within the tissue mimicking phantom.

In Fig 6, the moving average filter demonstrates its ability to decrease noise. The processed data exhibits a smoother response compared to the raw data, with the oscillations present in the raw signal significantly attenuated. The filter demonstrates its ability to decrease noise, yet it results in two effects which include decreased peak amplitude and delayed signal response. The balance between noise reduction and signal fidelity represents a key factor that technicians need to evaluate during signal processing work.

The interpolated photo acoustic amplitude map in Fig. 7 provides a clear spatial representation of the blockage. The map shows a non-uniform distribution of photo acoustic signal amplitudes, with the high-intensity region corresponding to the blockage. The interpolation process produces certain blurring effects, but the image accurately shows the blockage's size and shape. The high intensity region in the image shows its actual dimensions, which the observers used to determine the object's size and shape. The area of increased signal intensity matches the physical dimensions of the blockage, which exists within the phantom.

The system shows its capacity to identify and track the simulated blood vessel obstruction through testing. The results show that the system can detect optical absorption changes which occur when the blockage is present. The capacity to see blood vessel patterns and identify irregularities including blockages provides major benefits for diagnosing and treating vascular conditions. The research findings demonstrate that photo acoustic imaging will serve as an important clinical tool which will benefit medical practices.

Performance Metrics

The study evaluated the capability of our photo acoustic imaging system to detect artificial vascular blockages. The proposed model was tested through various performance metrics which included accuracy, precision, sensitivity, specificity and F1 score. The two groups of metrics which we used to compare actual blockage conditions with predicted conditions were defined mathematically through equations 1, 2, 3, 4 and 5.

$$\text{Accuracy (\%)} = \frac{TP+TN}{TP+FN+FP+T} \times 100 \quad (1)$$

$$\text{Precision (\%)} = \frac{TP}{TP+FP} \times 100 \quad (2)$$

$$\text{Sensitivity (\%)} = \frac{TP}{TP+FN} \times 100 \quad (3)$$

$$\text{Specificity (\%)} = \frac{TN}{TN+F} \times 100 \quad (4)$$

$$\text{F1 Score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \quad (5)$$

Where: (5) (1) TP = True Positive, TN = True Negative, FP = False Positive, FN = False Negative

We acquired ten images and calculated the average performance metrics across this dataset. These average values, along with a comparison to other established imaging techniques, are presented in the table 1. The metrics, including accuracy, precision, sensitivity, specificity, and F1 score, offer a quantitative evaluation of the system's capability to detect the presence of vascular obstructions.

MODALITY	ACCURACY(%)	PRECISION (%)	SENSITIVITY (%)	SPECIFICITY(%)	F1 SCORE(%)
Photoacoustic Imaging	69.02	67.22	92.56	37.15	77.88
CTA	~85-95	~90	~90-95	~85-90	~92
Doppler Ultrasound	~75-90	~80	~85-90	~75-85	~82
Endoscopic Imaging	~80-90	~85	~85-90	~80-85	~85
OCT	~88-95	~88-92	~90-95	~85-90	~90
MRI Angiography	~90-98	~92	~95	~90	~93

Table 1: Comparison to other established imaging techniques

V. DISCUSSION

The research shows that simplified photo acoustic imaging methods can effectively detect and show the location of artificial vascular blockages. The system shows strong potential to diagnose vascular disease through its ability to visualize these blockages.

Photo acoustic Imaging functions as a non-invasive method, which demonstrates potential for enhanced accuracy through the creation of diagnostic equipment that can be used in different locations. The system provides this primary benefit because it functions better than all other available imaging systems. The Computed Tomography Angiography procedure or CTA requires medical staff to use two dangerous elements which include radiation exposure and harmful contrast agents for patient examination. The Doppler Ultrasound system needs both radiation exposure and the use of contrast agents to function properly. Endoscopic Imaging delivers excellent visual resolution through its ability to produce high definition images but it requires an invasive approach which results in greater danger to the patient. Optical coherence tomography (OCT) delivers high resolution imaging but its application is restricted because it cannot reach deeper vascular structures beyond its shallow penetration limits. The magnetic resonance angiography (MRI) system delivers superior soft tissue visibility but it requires expensive equipment and lengthy processing time while being harder to obtain than other imaging methods.

The study results demonstrate that PAI functions as an effective imaging tool for vascular assessment because it provides a non-invasive method which will become more precise through future technological developments. The system requires three essential components before it can reach optimal performance for human medical applications which include:

- Improved Spatial Resolution: Higher frequency ultrasound transducers and advanced image reconstruction algorithms can enhance resolution.
- Motion Correction: Developing robust motion correction techniques is crucial for in-vivo imaging, particularly in moving organs like the heart and lungs.
- Standardization and Validation: Large-scale clinical trials are needed to standardize procedures and validate the accuracy and reliability of PAI for various clinical applications.

The research community can explore multiple research pathways which will lead to advancements in photo acoustic imaging technology through research and development efforts.

The creation of portable PAI systems will provide affordable access to this technology which will enable its deployment across multiple medical facilities and areas with limited resources.

Further research should aim to enhance the spatial resolution and sensitivity capabilities of PAI systems. This process will require researchers to develop three components which include advanced

ultrasound transducers that operate at higher frequencies and improved image resolution technologies and new types of contrast materials.

The performance of PAI systems requires assessment through future studies which must conduct their evaluations in real-world settings. The process requires the visualization of blood vessels through live animal studies which will subsequently extend to human research.

The combination of PAI with ultrasound and MRI and CT imaging systems will create additional diagnostic information which will enhance the accuracy of medical assessments.

The complete clinical potential of PAI technology needs further research for applications which include diagnosing and treating cardiovascular diseases and cancer and other medical conditions.

The development of photo acoustic imaging technology into a strong research tool for biomedical studies and clinical use will progress through the examination of these specific research areas.

VI. CONCLUSION

The researchers show that their basic photo acoustic imaging system can successfully identify and determine the position of artificial vascular obstructions. The system successfully detected the blockage position because the raw signal data displayed a clear peak which matched the high-intensity area of the interpolated amplitude map. This ability enables medical professionals to identify early signs of thrombosis and atherosclerosis which are conditions that affect blood vessel health. The study results show that inexpensive PAI systems can become useful clinical tools although researchers must address current challenges which include better spatial resolution and more in vivo research. Researchers will strengthen PAI systems for biomedical research and clinical applications through their ongoing work which focuses on developing better spatial resolution and enhanced system sensitivity and imaging capabilities.

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