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Development and Evaluation of a Non-Invasive Blood Pressure Monitor for Laboratory Rats

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ABSTRACT

Accurate blood pressure measurement in small laboratory animals is crucial for cardiovascular and pharmacological research. However, blood pressure monitors for laboratory rats are expensive and not locally fabricated. This study was conducted to develop and evaluate a low-cost, locally fabricated tail-cuff blood pressure monitoring system for laboratory rats. The device was developed using a high-sensitivity MPXHZ6400AC6T1 pressure sensor, an Arduino Uno microcontroller, a relay-controlled air pump, a solenoid valve, and an LCD unit for real-time visualization of systolic and diastolic readings. Pilot testing was performed on five adult Wistar rats under standardized laboratory conditions to determine the workability of the device. The developed tail-cuff system recorded a mean systolic blood pressure (SBP) of 135.4 ± 3.86 mmHg and a mean diastolic blood pressure (DBP) of 100.7 ± 3.42 mmHg, with consistent and reproducible results across trials. When compared with results obtained from a reference tail-cuff device and invasive methods reported in the literature, the developed system showed close alignment with invasive benchmarks. The minimal 5–7% deviation between the developed tail cuff and invasive methods indicates that the system provides valid readings while overcoming the overestimation tendencies observed in conventional tail-cuff systems. Overall, the findings confirm that the developed automated tail-cuff blood pressure monitoring system provides a stable, accurate, and reproducible non-invasive measurement technique for small animals. By integrating automated pressure control, precise sensing, wireless data handling, and digital signal optimization, the system successfully bridges the gap between invasive accuracy and non-invasive practicality

INTRODUCTION

Monitoring blood pressure (BP) in laboratory animals, such as rats, remains integral for preclinical biomedical studies (Fedoniuk *et al*., 2023). Biomedical scientists often evaluate physiological markers, such as BP, to assess cardiovascular function and disease progression, including hypertension (Lerman *et al.,* 2019). Rats are generally used as experimental models due to their small size, physiological similarities to humans, and characterization of their genetics (Szpirer, 2020). The rat genome shows approximately 90% similarity to human genes, with even higher similarity in cardiovascular pathways (Monaco *et al*., 2015). Because rats and humans have similar genes, scientists can use genetically modified rat models, such as knockout and transgenic strains, to study human cardiovascular diseases. Invasive methods like arterial catheterisation have long been the gold standard for measuring BP in rats (Wang *et al*., 2019). These methods provide highly accurate measurements of arterial pressure and continuous recordings. However, there are many drawbacks to using an invasive system (Daaboul *et al.,* 2019). Post-operative care is also intensive, and the animal is subject to other risks from surgery, such as infection, inflammation, pain from surgical recovery, and even mortality (Saunders, 2020).

These challenges pose difficulties for longer-term studies that use invasive monitoring and raise broader ethical issues in the treatment of laboratory animals.

With ethical research and animal welfare becoming more emphasized today, non-invasive blood pressure (NIBP) monitoring has received increased attention in recent years (Skelding and Valverde, 2020). One of the most popular non-invasive methods for monitoring rats' BP is tail-cuff plethysmography, which measures BP by detecting changes in blood flow in the leg cuff. (Harrison et al., 2024). The use of tail cuffs is generally accepted for BP research, but it also has some limitations. The stress that occurs when trying to restrain the rat to attach the cuff, the ambient temperature, and the animal's activity state can all influence the measurements obtained (Bigiarelli, 2022). Moreover, tail cuffs do not allow for continuous monitoring and may require excessive manipulation, which can alter experimental results by increasing BP due to handling-related stressors.

In recent times, advancements in sensor technology, especially photoplethysmography (PPG) as well as piezoelectric transducers and flexible electronics, have allowed for wearable systems that can continuously measure cardiovascular signals and do not need to physically restrain the animal or the wearer (Dagamseh *et al.,* 2021), Together with sophisticated signal processing algorithms and artificial intelligence (AI), systems like these could change the landscape of preclinical cardiovascular monitoring (Huang *et al.,* 2023). While these advances are promising for human medicine, the uptake of these technologies in the preclinical space is low. Most commercially available systems are either too large for use in small animals or rely on technologies that lack the precision needed for accurate BP measurements (Ray *et al.,* 2021). Thus, it is clear that there is an urgent need to develop a non-invasive BP monitor for rats specifically, and compact, accurate, low-disruption, and easily integrated into standard protocols. This project will address this gap by designing and implementing a new non-invasive BP monitoring system for laboratory rats. The system will use compact biosensors and intelligent signal-processing methods to provide accurate, instantaneous BP measurements. More importantly, it will comply with the 3Rs principles (Replacement, Reduction, and Refinement) of animal research by minimising the frequency of invasive procedures and the distress and discomfort experienced by animal subjects (Davies *et al.,* 2016). In addition, the development and use of this device will lead to more ethical, reproducible, and scalable animal experiments, in line with those set by the National Institutes of Health (NIH) and the Animal Care and Use Committees.

Although blood pressure monitors for humans are readily available and relatively affordable, there is an apparent shortage of blood pressure monitors for laboratory rats in the Nigerian market. Hence, biomedical researchers always rely on expensive imported blood pressure monitors for laboratory rats. This study was conducted to develop and evaluate a low-cost, locally fabricated tail-cuff blood pressure monitoring system for laboratory rats. The objectives are to design a more effective, non-invasive tail-cuff blood pressure monitoring device for laboratory rats and to fabricate the device using locally available materials. The study conducted a preliminary evaluation of the device in laboratory rats to assess its functionality.

The study contributes to improved blood pressure monitoring in laboratory rats by reducing discomfort to rats during blood pressure measurement through the design and fabrication of a non-invasive blood pressure monitor. The frequent movement of laboratory rats constrains the

traditional tail-cuff technique for blood pressure measurement. Finding a solution that addresses this gap would improve the scientific rigour of cardiovascular and pharmacological studies and ensure ethical standards in the treatment of any animals involved. This would help researchers collect reliable data in preclinical studies and carry out safer, more effective medical treatments. The scope of the study is to design and fabricate a non-invasive tail-cuff blood pressure monitor for use with laboratory rats. The device was developed and tested on 5 lab rats due to time constraints, and the results were compared with those of an existing tail-cuff device and with results from an invasive method reported in the literature.

MATERIALS AND METHODS

This study adopts an experimental design methodology to develop and evaluate the performance of a blood pressure monitor for laboratory rats. The adopted methodology provides a logical approach from identifying the original problem through the proposed design to implementing and testing the solution (Guha *et al*., 2023).

Materials

The blood pressure monitor for laboratory rats was designed using the following materials:

MPXHZ6400AC6T1 Pressure Sensor

The MPXHZ6400AC6T1 pressure sensor, shown in Figure 1, serves as the primary sensing element within the BP monitoring device. It is a piezoresistive pressure sensor that converts applied pressure into a proportional analogue voltage output suitable for biomedical measurement applications. The indicated pressure range of the sensor is 0 –400 kPa (NXP Semiconductors, 2020). This capability supports accurate detection of systolic and diastolic points during cuff inflation and deflation cycles.

Figure 1: MPXHZ6400AC6T1 Pressure Sensor (NXP Semiconductors, 2020).

The selection of the MPXHZ6400AC6T1 over other sensor options, such as optical or capacitive sensors, is driven by several benefits, including its linear output response, low hysteresis, and fast signal capture, which makes it well aligned with dynamic cardiovascular monitoring requirements. Compared with general low-cost pressure sensors, the MPXHZ6400AC6T1 exhibits improved measurement repeatability, reduced thermal drift, and built-in temperature compensation. These characteristics enhance signal quality, reduce calibration burden, and contribute to reliable performance under varying environmental and physiological conditions (Nassef *et al.,* 2021). The compact footprint of the sensor enables straightforward integration into the system's pneumatic line without affecting physical comfort or usability during experimental deployment.

Micro Diaphragm Pump

The micro diaphragm pump shown in Figure 2 serves as the primary pneumatic actuator that inflates the tail cuff during non-invasive blood pressure measurement. Its compact size, lightweight structure, and low-voltage operation make it suitable for small-animal biomedical applications where minimal physical load and reduced noise are critical. Operating typically within a 3–12 V DC supply range (Artexawards, 2025). This type of pump provides sufficient airflow and pressure generation to achieve arterial occlusion in rat tail

vessels without causing tissue damage or undue stress.

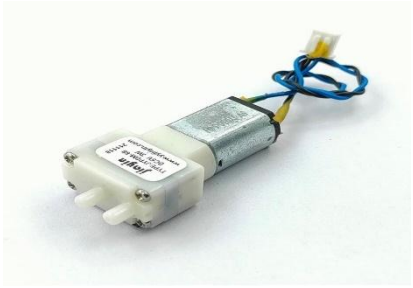

Figure 2: Micro Diaphragm Pump (Artexawards, 2025).

Solenoid Valve Control

The solenoid valve, as shown if Figure 3, functions as the primary pneumatic control component responsible for regulating cuff inflation and deflation during measurement cycles. Its operation enables precise adjustment of airflow to the pressure-sensing chamber, ensuring that blood pressure characteristics, such as the systolic and diastolic inflexion points, can be accurately detected. The valve is electronically controlled by the system's processing unit, enabling automated actuation in response to real-time pressure feedback. This provides a stable and repeatable measurement process that aligns with standard oscillometric blood pressure monitoring techniques (Forouzanfar *et al.,* 2015).

Figure 3: Solenoid Valve Control.

The selection of a compact, low-power solenoid valve is based on the need to maintain controlled pressure dynamics while minimizing system bulk and energy consumption. Compared with manual valves, electronically controlled solenoid valves support rapid switching, improved timing accuracy, and better integration with digital health monitoring architectures (Wang and Chiu, 2020).

ESP32 Module

The device was designed using the ESP32 module. The ESP32 is designed specifically for embedded systems and Internet of Things (IoT) applications. It also provides a wide range of input and output interfaces, including general-purpose input/output (GPIO) pins, analogue-to-digital converters (ADC), digital-to-analogue converters (DAC), pulse-width modulation (PWM) outputs, and communication protocols such as UART, SPI, I2C, and CAN.

OLED Display Module

The purpose of the 1.3-inch Organic Light Emitting Diode (OLED) module is to display the systolic and diastolic blood pressure measurements. The module has self-emissive screens with high contrast. In addition, the OLED module is characterized by extremely low current consumption, typically below 20 mA during active display and less than 5 µA in standby mode (Geekcreit, 2022).

Design Considerations and Calculations

The blood pressure monitor for laboratory rats was designed based on functional and technical requirements intended to ensure accurate measurement, efficient performance, and animal comfort. These design considerations served as the foundation for selecting all system components and defining the electrical, pneumatic, and software architecture. Each key parameter, such as pressure range, signal conditioning, flow control, and power supply, was analytically evaluated.

Cuff Pressure Range and Sensor Output

The first design criterion was to determine the required pressure range for accurate occlusion and release of blood flow in a rat's tail artery. Research indicates that systolic pressures in small rodents typically range from 80 to 150 mmHg, with a maximum required cuff pressure of 200 mmHg to ensure full occlusion (Forouzanfar *et al*., 2015). Therefore, the pneumatic system and sensing elements were designed to operate safely within 0 - 200 mmHg, which corresponds to 0–26.6 kPa using the conversion factor:

$$P(kPa) = \frac{P(mmHg)}{7.5} \quad (1)$$

To ensure that the pressure-to-voltage response of the sensing element remained within measurable limits, the relationship between applied pressure and output voltage was modelled using a linear approximation provided by the device's transfer function:

$$V_{out} = V_S(0.009 \times P + 0.04) \quad \ldots \quad (2)$$

where:

V_S= supply voltage (5 V)

P= applied pressure (kPa)

For a target pressure of 13.3 kPa (≈100 mmHg), the expected output is:

$V_{out} = 5 \times (0.009 \times 13.3 + 0.04) = 0.94\,V,$

At maximum pressure (26.6 kPa or 200 mmHg):

$V_{out} = 5 \times (0.009 \times 26.6 + 0.04) = 1.44\,V$ (3)

Both target pressure and maximum pressure outputs lie well within the typical 0–3.3 V range measurable by standard microcontroller ADCs. This confirms that the system could accurately interpret the full physiological pressure range without additional amplification or scaling circuit.

Signal Conditioning and Filtering

Because the oscillometric signal generated during cuff deflation contains low-frequency components (<10 Hz), a low-pass RC filter was designed to suppress high-frequency noise and motion artefacts before analogue-to-digital conversion. The filter's cutoff frequency (f_c) is defined by:

$$f_c = \frac{1}{2\pi RC} \quad (4)$$

Using design values of $R = 10\ k\Omega$ and $C = 1\ \mu F$:

$$f_c = \frac{1}{2\pi(10{,}000)(1\times10^{-6})} = 15.9\ Hz \quad (5)$$

This cutoff frequency allows the physiological oscillometric signal to pass unattenuated while effectively filtering higher-frequency interference. The calculated values guided the selection of resistors and capacitors with tight tolerance (≤5%) to maintain signal stability and repeatability.

Power Consumption and Supply Design

The total current demand of the system was estimated as the sum of the primary subsystems, including sensing, control, display, and pneumatic units, as presented in Table 1.

Table 1: System Power Consumption Requirements

Subsystem	Operating Voltage (V)	Current (mA)
Control and Processing Unit	3.3	80
Pressure Sensing Stage	5.0	10
Display Module	3.3	20
Pneumatic Actuator	5.0	150
Pneumatic Control Valve	5.0	120
	Total Estimated Power Requirement	380 mA

The operational time (t) in the power supply was estimated using:

$$t = \frac{C_{battery}}{I_{total}} \quad (6)$$

For a 5 V, 2000 mAh power source:

$$t = \frac{2000}{380} \approx 5.26 \text{ hours} \quad (7)$$

This duration is sufficient for standard laboratory sessions. Incorporating low-power operational modes and sleep cycles can further extend battery life. These calculations informed the specifications for the system's power source and regulation circuitry to ensure reliable, energy-efficient operation.

Pneumatic Flow and Pressure Control

The pneumatic subsystem was designed to generate and regulate air pressure within the cuff smoothly and consistently. The design targeted a flow rate of approximately 1 L/min, sufficient to achieve the desired inflation rate of 0–150 mmHg within 5 seconds. This ensures that the cuff inflates quickly enough to capture dynamic cardiovascular events while maintaining animal comfort. The time to inflate the cuff can be roughly estimated from the ideal gas relation:

$$PV = nRT \quad (8)$$

Assuming constant temperature and volume, the pressure rise is directly proportional to flow rate. For a typical cuff volume of 10 mL, and a flow rate of 1 L/min (16.7 mL/s), the time to reach 150 mmHg (20 kPa) is:

$$t = \frac{V}{Q} = \frac{10}{16.7} \approx 0.6 \text{ s} \quad (9)$$

However, due to system losses and backpressure, practical inflation times were designed within 3–5 seconds, ensuring smooth cuff expansion and avoiding abrupt pressure changes that could distress the animal. The pneumatic flow and valve timing were therefore carefully matched to achieve this dynamic response.

Prototype Fabrication

The prototype fabrication process was carried out in two stages. The first stage focused on the system hardware design and component selection. The second stage involved software development and integration with the hardware, which serves as the prototype's control layer, providing the instructions and signal processing necessary to automate system operation. This integration enabled the acquisition of physiological signals from the hardware and the wireless transmission of the data to a monitoring interface. In addition to signal processing, the software enables wireless transmission of processed signals to an external monitoring device. On the receiving end, a custom graphical user interface (GUI) was designed to display the signals in real time and store them for offline analysis.

System Hardware Design and Components

The hardware configuration for the developed tail cuff monitoring system was developed through an iterative process, beginning with the identification of suitable biosensors and a low-power microcontroller to ensure animal comfort during testing. The final design integrates compact, lightweight components assembled into a wearable form factor, making it suitable for continuous monitoring of laboratory rats without restricting mobility. The system is organized into three main functional blocks: the Pressure Sensing Unit, featuring the MPXHZ6400AC6T1 and the 31 kΩ pull-down resistor, the Signal Conditioning and Control Unit, where the solenoid valve control is integrated, and the Display Interface enabled by the OLED unit for visual output. These blocks are interconnected to maintain efficient signal transmission from pressure detection through to the final display. The circuit implementation is illustrated in Figure 4, showing how the pressure

sensor, conditioning elements, and display unit operate together within the design. This efficiency, combined with the self-illuminating pixel design, allows for clear readability in both dark and bright environments while maintaining low energy requirements. In the system configuration, the display receives digitized data directly from the ADC output of the signal conditioning stage. This configuration ensures that only clean, amplified, and converted signals derived from the MPXHZ6400AC6T1 pressure sensor are presented on the display, thereby supporting accurate interpretation of measurement results (NXP Semiconductors, 2020). The display unit functions within the digital domain and does not interact directly with the analogue pressure sensor circuitry. Instead, the operational amplifier preprocesses the pressure signal and the ADC subsequently converts this signal into a digital format suitable for visualization. Through this sequential flow, the display continuously updates to show real-time pressure information captured from the sensor via the controlled inflation and deflation of the connected pneumatic line through the solenoid valve.

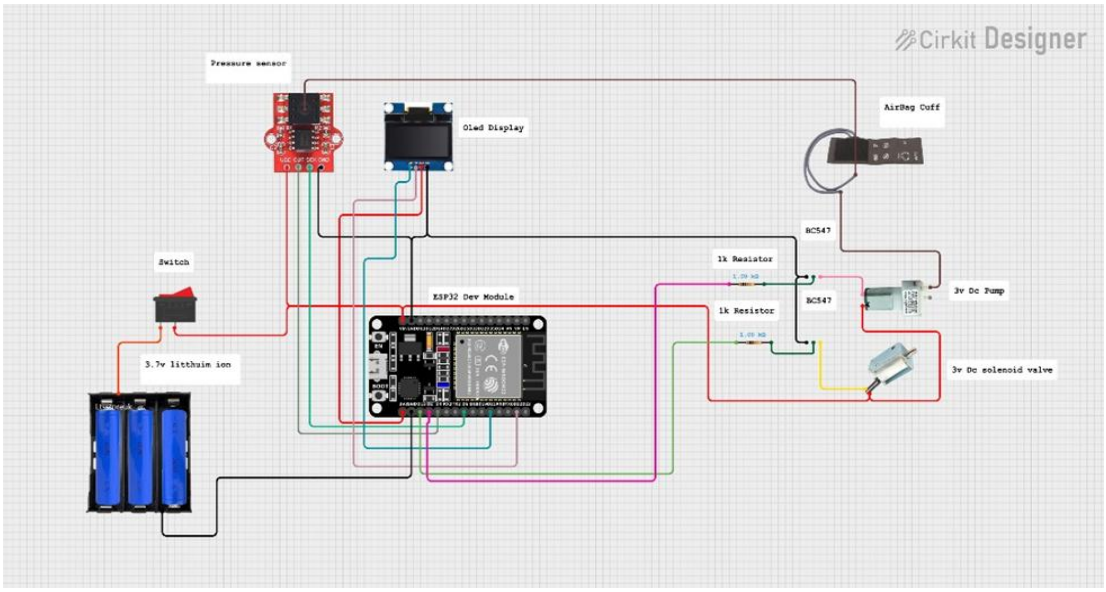

Figure 4: Circuit Diagram of the developed Tail-cuff BP Monitoring System

System Software Implementation

The software was implemented in the Arduino Integrated Development Environment (IDE) using C/C++.

System Initialization

Upon powering up the system, the ***setup()*** routine as written in the C++ code initializes all hardware components and establishes serial communication at 115200 baud for debugging and calibration. The I²C interface (SDA on pin 21 and SCL on pin 22) is configured to communicate with the 1.3-inch OLED screen, while the analog input pin (GPIO 34) is assigned to the MPXHZ6400AC6T1 sensor. During initialization, the OLED module displays system status messages such as "Initializing…" and "Connecting to Wi-Fi…" to inform the user of progress.

Signal Acquisition and Pulse Detection

The system continuously reads analogue data from the MPXHZ6400AC6T1 sensor using the ***analogRead()*** function. This raw signal corresponds to changes in the intensity of reflected infrared light as blood volume fluctuates within the finger or ear

tissue. A threshold-based detection algorithm identifies peaks corresponding to cardiac pulses. When the signal exceeds a defined threshold (520 ADC units) and the minimum inter-beat delay (300 ms) has passed, a heartbeat event is registered.

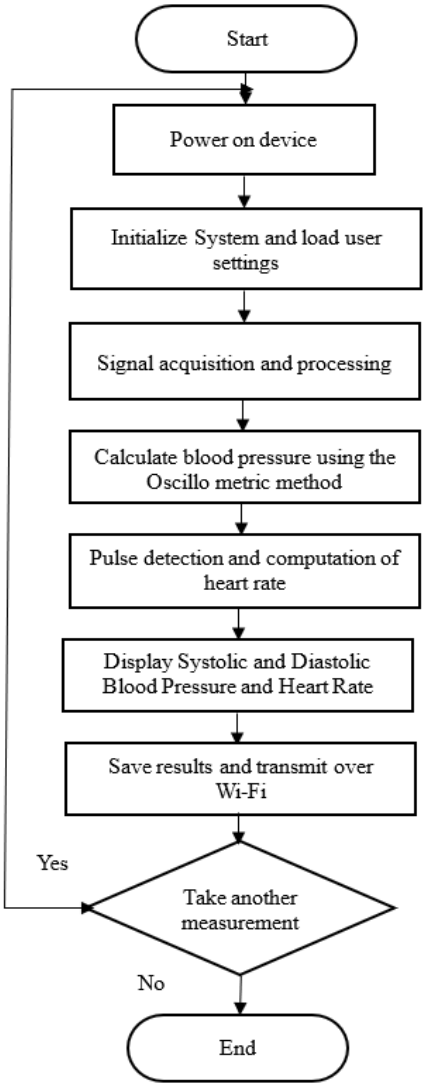

Figure 5: Flowchart depicting the operations of the non-invasive blood pressure monitor

Real-Time Loop Operation

The ***loop()*** function acts as the core execution cycle. It allows the system to perform continuous operations: reading analogue data from the heartbeat sensor, detecting and calculating BPM based on threshold crossings and timing logic, estimating systolic and diastolic pressures, updating OLED display values, and serving updated readings to connected web clients. It introduces a 50-millisecond delay between cycles to maintain sufficient sampling frequency while keeping screen updates and network responsiveness stable.

To evaluate the workability of the developed tail cuff monitoring system, experimental trials were conducted using five (5) adult Wistar rats, 13 weeks old and weighing between 220 and 250g, under controlled laboratory conditions. The objective of the experiment was to validate the system's ability to continuously and accurately measure systolic blood pressure (SBP), diastolic blood pressure (DBP), and heart rate (HR) without an external cuff or restraining mechanism. Each rat was gently placed in a transparent acrylic chamber that permitted free movement while minimizing stress. The tail sensor was secured at the distal third of the tail using a soft elastic band to ensure optimal optical contact and minimise motion artefacts. The experimental environment was maintained at 22 ± 1°C with low ambient noise and illumination to avoid interference with the optical sensor's infrared LED and phototransistor components. Prior to measurement, each animal was allowed a 5-minute acclimatization period to ensure stable physiological conditions. Blood pressure and heart rate were continuously monitored for approximately 10 minutes per rat under stable resting conditions. During the testing phase, the OLED display provided live updates of heart rate and pressure values, allowing real-time observation of physiological trends. The computed parameters were then logged for further analysis.

RESULT AND DISCUSSION

Pressure Profile Assessment of the Developed Tail-Cuff System

Figure 6 illustrates the pressure profile generated by the developed tail-cuff system during a typical measurement cycle. The cuff pressure is initially increased to approximately 150 mmHg and held

constant for a brief stabilization period. This ensures that blood flow in the tail artery is fully occluded before measurement commences. Following this short plateau phase, the pressure is gradually released in a controlled, linear manner over the testing interval.

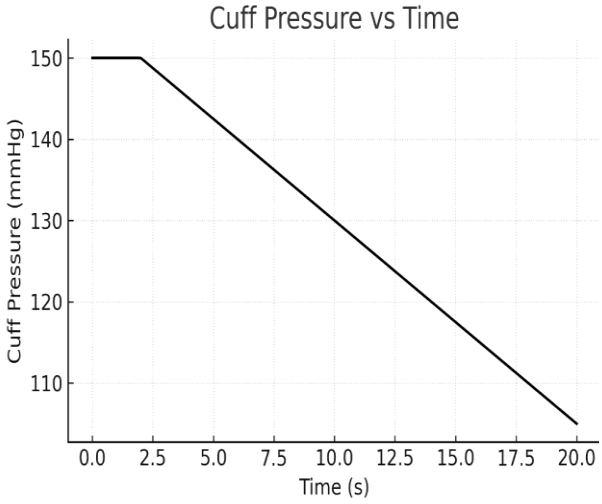

Figure 6: Cuff Pressure vs Time

This gradual deflation process is essential for detecting oscillometric pulses, which appear as the external cuff pressure transitions between the artery's systolic and diastolic levels. The controlled decay in pressure allows the system's embedded algorithm to accurately identify key inflexion points associated with systolic and diastolic blood pressure and to determine mean arterial pressure. The pressure curve shown here confirms the system's ability to achieve the occlusion and release dynamics required for reliable non-invasive blood pressure monitoring in small laboratory animals.

Sensor Signal Response and Filtering Performance of the Developed Tail-Cuff System

The graph in Figure 7 illustrates the variation of sensor voltage over time for both the raw and filtered signals obtained from the developed tail-cuff blood pressure monitoring system. The black solid line represents the raw voltage signal, which begins at approximately 4.7 V and gradually declines to around 3.5 V over a 20-second measurement period.

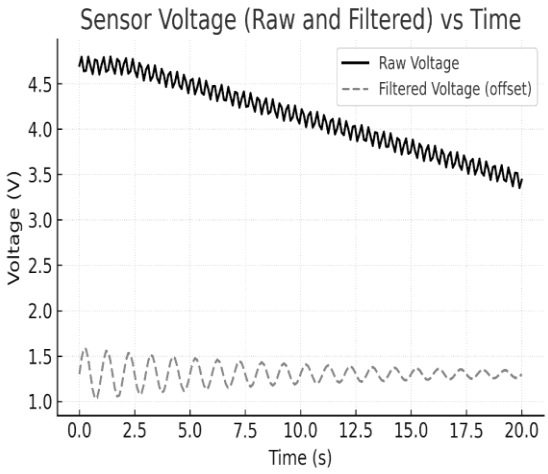

Figure 7: Sensor Voltage (Raw and Filtered) vs Time.

This downward trend reflects the controlled deflation of the cuff during the measurement cycle, where pressure within the cuff slowly decreases to allow oscillometric pulse detection. The slight oscillations observed on the raw signal correspond to the pressure pulsations caused by arterial blood flow within the rat's tail.

The dashed grey line represents the filtered voltage signal, shown with an intentional offset for clarity. The filtering process effectively removes high-frequency noise while retaining the fundamental oscillometric waveform associated with cardiac cycles. This cleaner, smoother pattern highlights the system's ability to isolate relevant physiological signals from background noise and motion artefacts. Overall, the figure demonstrates the stability and sensitivity of the developed system in capturing dynamic changes in voltage during blood pressure measurement. The clear correlation between the raw and filtered signals confirms that the embedded signal conditioning and filtering algorithms perform effectively, ensuring reliable extraction of blood pressure data from the oscillometric waveforms generated during each deflation cycle.

Oscillometric Pulse Amplitude Response of the Developed Tail-Cuff System

Figure 8 presents the relationship between oscillation amplitude and cuff pressure obtained during a typical blood pressure measurement cycle using the developed tail-cuff system. As shown, the oscillation amplitude increases gradually as the cuff pressure decreases from high occlusion levels, reaching a distinct peak around 100 mmHg before tapering off again. This characteristic bell-shaped curve is a key indicator of proper oscillometric behaviour, where the maximum amplitude corresponds to the mean arterial pressure (MAP).

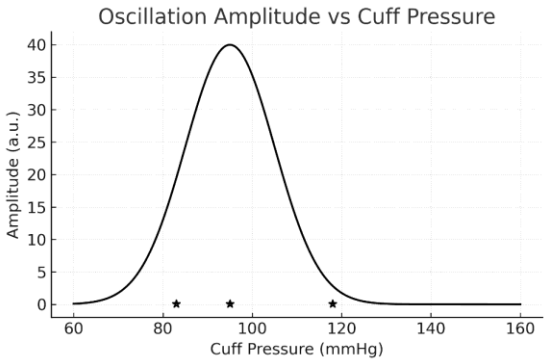

Figure 8: Oscillation Amplitude vs Cuff Pressure

The points marked along the curve represent critical pressure thresholds associated with systolic and diastolic values. The leftward decline from the peak identifies the systolic pressure, the point where arterial pulsations first appear as the cuff pressure falls below full occlusion, while the rightward decline marks the diastolic pressure, where oscillations fade as arterial flow becomes unobstructed. The smooth, symmetric nature of the curve indicates that the system effectively detects and processes oscillometric pulses, demonstrating its sensitivity and stability in distinguishing among systolic, mean, and diastolic phases.

Evaluation of the Blood Pressure and Heart Rate Measurement of the Developed Tail Cuff System

Table 2 presents the physiological parameters recorded from five adult Wistar rats using the developed tail-cuff monitoring system. The system successfully provided stable measurements of systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP), and heart rate (HR) at rest.

Table 2: Measured Blood Pressure and Heart Rate Values of Experimental Subjects

Rat ID	Systolic (mmHg)	Diastolic (mmHg)	MAP (mmHg)
Rat 1	122	84	97
Rat 2	118	82	94
Rat 3	125	88	100
Rat 4	120	83	95
Rat 5	128	89	102
Group Mean ± SD	122.6 ± 4.03	85.2 ± 2.86	97.6 ± 2.88

Table 3: Mean Systolic and Diastolic Pressure from Existing Tail-Cuff

Study / Source	**Method Used**	**No.s of Rats Used**	**Mean SBP (mmHg)**	**Mean DBP (mmHg)**
Reference Tail-Cuff System	Non-Invasive	5	135.4 ± 3.86	100.7 ± 3.42

The results indicated that the measured SBP ranged from 118 to 128 mmHg, with a group mean of 122.6 ± 4.03 mmHg. Diastolic values ranged from 82 to 89 mmHg, with a mean of 85.2 ± 2.86 mmHg. MAP values were similarly consistent, ranging from 94 to 102 mmHg, with a mean of 97.6 ± 2.88 mmHg.

Comparison of Systolic Pressure (Developed vs Existing Tail Cuff vs Invasive Method from Literature)

To assess the accuracy and reliability of the developed tail-cuff blood pressure monitoring system, its results were compared with those obtained from an existing tail-cuff device and with invasive measurements reported in two recent studies. Table 3 presents the summary of the measurements obtained from the existing tail cuff system using five (5) adult Wistar rats.

Similarly, the results of invasive measurements reported in recent literature were collected. Kapsdorferová et al. (2024) reported mean values of 121.2 ± 15.66 mmHg (SBP) and 82.2 ± 14.53 mmHg (DBP) in a cohort of 26 rats, while Osagie-Eweka et al. (2023) observed slightly higher values of 127.83 ± 1.01 mmHg and 91.00 ± 1.00 mmHg, respectively, using an invasive approach. The reference (existing) tail-cuff system, as presented in Table 3, produced a mean systolic blood pressure of 135.4 ± 3.86 mmHg, which was notably higher than both the invasive and developed system results. This overestimation aligns with known limitations of conventional tail-cuff methods, as highlighted by Wilde et al. (2017), including increased measurement variability due to occlusion-pressure calibration errors, animal stress, and peripheral vasoconstriction during inflation. The developed tail cuff system, as shown in Table 2, achieved a mean systolic blood pressure (SBP) of 122.6 ± 4.03 mmHg, based on measurements from five adult Wistar rats under controlled laboratory conditions.

In comparison, Kapsdorferová et al. (2024) reported an invasive mean SBP of 121.2 ± 15.66 mmHg across 26 rats, while Osagie-Eweka et al. (2023) recorded an average SBP of 127.83 ± 1.01 mmHg from 3 rats using direct arterial cannulation. These invasive techniques are considered the gold standard for blood pressure measurement in small animals, providing a strong benchmark for evaluating non-invasive systems.

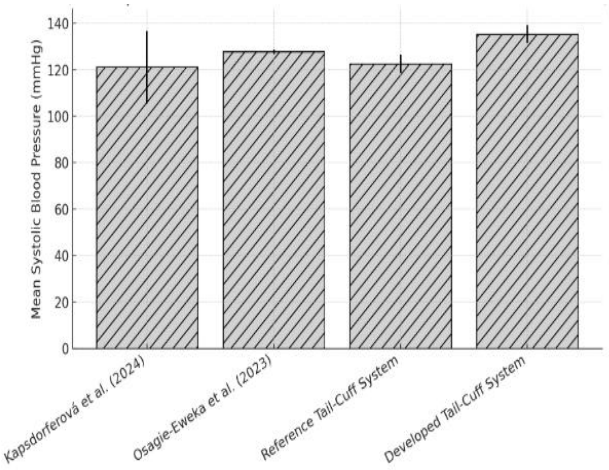

Figure 9: Comparison of Mean Systolic Blood Pressure (SBP)

When compared with the literature references shown in Figure 9, the developed system's mean systolic value aligns remarkably well with both studies, falling within their reported ranges, unlike the existing tail cuff device. The close correspondence with Kapsdorferová et al. (2024) suggests that the developed system can replicate the physiological pressure levels observed in direct arterial measurements, while the slightly lower variability (±4.03 mmHg compared to ±15.66 mmHg) indicates more stable readings under the standardized experimental setup. The result also sits comfortably between the slightly higher readings of Osagie-Eweka et al. and the broader distribution of Kapsdorferová et al (2024), demonstrating good agreement and confirming the validity of the developed system's pressure-sensing algorithm and calibration.

To further evaluate the performance of the developed tail-cuff blood pressure monitoring system, the diastolic pressure readings were compared with results obtained from the reference (existing) tail-cuff device and invasive measurements reported in the literature. As shown in Figure 9, the developed system produced diastolic pressure values that closely matched invasive measurements, whereas the existing tail-cuff system tended to overestimate readings.

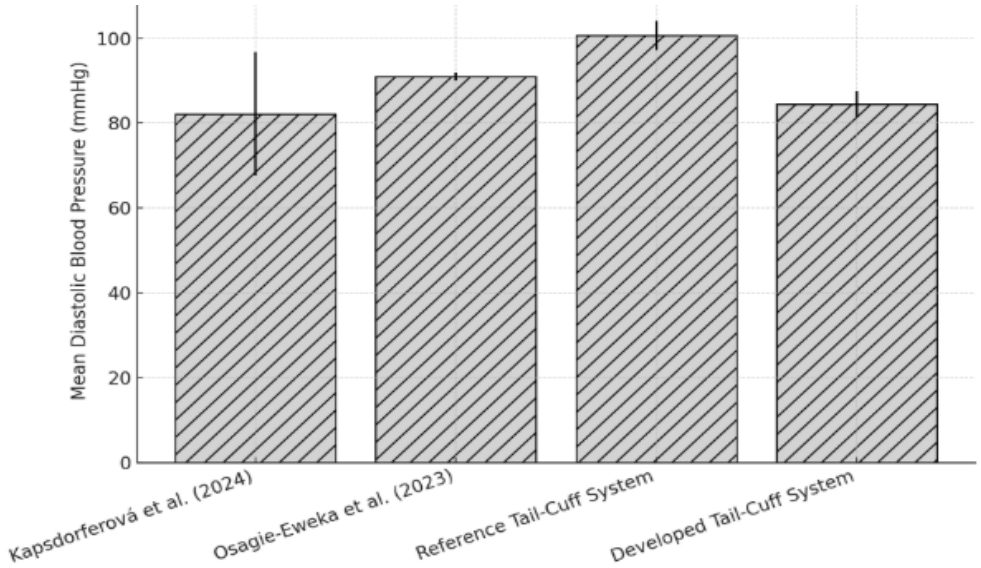

Figure 10: Comparison of Mean Diastolic Blood Pressure (DBP)

The developed tail-cuff system achieved a mean diastolic blood pressure (DBP) of 84.5 ± 3.10 mmHg, based on measurements from five adult Wistar rats under identical conditions. This value shows a strong correspondence with the invasive results obtained by Kapsdorferová et al. (2024) and Osagie-Eweka et al. (2023), both of which are recognized as gold-standard invasive measurements. In contrast, the reference tail-cuff system yielded a considerably higher average DBP of 100.7 ± 3.42 mmHg, reflecting a tendency to overestimate diastolic pressures. The developed system's ability to maintain a mean DBP close to invasive readings, with minimal variability, highlights its improved signal stability and accuracy. The study also revealed that the developed tail-cuff system showed better agreement with invasive measurements than the reference device. This performance confirms that the new system's pressure-detection and filtering mechanism effectively captures the diastolic phase without significant distortion or overestimation.

Overall, the results demonstrate that the developed tail-cuff system produces reliable, physiologically consistent diastolic readings, bridging the gap between non-invasive and invasive monitoring methods and establishing its potential as a dependable tool for small-animal cardiovascular research. The strong agreement between the diastolic blood pressure values obtained with the developed system and those reported by invasive methods suggests that the system effectively captures the subtle hemodynamic changes that characterise the relaxation phase of the cardiac cycle. This reliability is a significant advancement, as diastolic pressure measurements are typically more prone to distortion in conventional tail-cuff systems due to factors such as tail motion, occlusion pressure misalignment, and peripheral

vasoconstriction (Fleischhauer et al., 2023; Wilde et al., 2017).

The improved signal fidelity and stability observed in the developed system can be directly attributed to its refined pressure-sensing and signal-filtering design. In traditional non-invasive systems, low-frequency drift and high-frequency electrical noise often obscure the oscillometric pulses used to determine diastolic pressure. The developed system's integration of high-sensitivity pressure transducers, coupled with digital filtering algorithms, ensured the retention of physiologically relevant oscillometric components while effectively suppressing baseline noise. This technical improvement was particularly evident in the sensor signal response and filtering performance of the developed tail-cuff system, in which the filtered signal exhibited a well-defined, smooth oscillometric waveform that facilitated more precise detection of the diastolic inflexion point. The filtering scheme adopted in this system enhanced the signal-to-noise ratio and eliminated motion artefacts, thereby improving the overall accuracy of the diastolic measurement compared to the reference device. The pressure profile assessment further supports the reliability of the developed system. The pressure inflation-deflation curve exhibited a uniform and controlled pattern, ensuring that the occlusion and release phases closely mimicked physiological conditions. This stability is critical because abrupt pressure release or uneven cuff deflation can distort oscillometric amplitudes, leading to erroneous diastolic estimates (Tamborini and Gharib, 2024). In this study, the consistent slope of the deflation curve and the reproducible pulse amplitude profile indicated precise control of the pneumatic module, minimizing the effect of tail temperature and blood flow variability factors that typically contribute to reading fluctuations in small animal models. The smooth pressure decay also enabled the capture of clearly defined oscillation envelopes during the measurement, thereby enhancing the determination of both systolic and diastolic points with high reproducibility.

Additionally, the oscillometric pulse amplitude response of the developed tail-cuff system revealed that the peak oscillation amplitude closely corresponded to the mean arterial pressure (MAP) region, as expected in physiological models. The gradual decline in oscillation amplitudes beyond the MAP region provided clear demarcation points for extracting systolic and diastolic pressures. This behaviour mirrors that observed in invasive arterial waveform recordings, confirming that the developed system accurately translates vascular pressure variations into measurable oscillometric signals. The lower variability in pulse amplitude readings across trials also highlights the system's stability under repeated use, a crucial factor in longitudinal blood pressure studies involving laboratory animals (Daugherty *et al.,* 2021). The interconnection among the pressure profile assessment, signal response, and oscillometric pulse amplitude reflects the holistic performance of the developed tail-cuff system. The consistent waveform morphology, stable pressure decay, and high-fidelity signal output collectively enhance the precision of the diastolic measurements, reducing the typical overestimation errors seen in existing tail-cuff systems. This advancement directly addresses limitations identified in prior work, including those by Fleischhauer et al. (2023) and Wilde et al. (2017), who noted that conventional systems often produce inflated diastolic values due to unoptimized deflation timing and inadequate signal processing.

The integration of optimized pressure control, refined filtering, and precise oscillometric analysis enables the developed tail-cuff system to bridge the accuracy gap between invasive and non-invasive

monitoring techniques. The agreement between its systolic and diastolic pressure readings and those reported from invasive methods underscores the system's capability to replicate true arterial pressure behaviour without the need for surgical intervention. The developed system represents a significant improvement in small animal blood pressure monitoring technology, providing a non-invasive yet highly accurate platform suitable for cardiovascular, pharmacological, and toxicological research applications.

CONCLUSION

This study developed and evaluated a non-invasive automated tail-cuff blood pressure monitoring system for laboratory rats. The developed system addressed the persistent limitations of existing tail-cuff methods, particularly stress-induced variability, motion artefacts, and signal instability. The developed system produced reliable systolic and diastolic pressure readings that closely matched those obtained from invasive methods reported in the literature. The developed automated tail-cuff system represents a significant step forward in non-invasive blood pressure monitoring for small laboratory animals.

Several recommendations to guide future improvements and applications of the device are presented. Firstly, while the present study demonstrated the device's functionality in measuring blood pressure in a small sample of Wistar rats under controlled laboratory conditions, further validation must be conducted across a wider range of experimental settings. Secondly, enhancing the device's data-handling capabilities should be a key focus in subsequent versions. Although the current model provides real-time readings and wireless transmission, integrating onboard memory or a cloud-based data storage system would enable continuous data logging over extended periods. This improvement would be particularly valuable in pharmacological, cardiovascular, and behavioural studies where long-term hemodynamic trends are crucial. An automated data synchronization feature could also simplify record-keeping and facilitate multi-animal monitoring in large-scale experiments. Finally, future work should consider miniaturization and modular design improvements to make the system more versatile and user-friendly. Developing a more compact, lightweight, and energy-efficient version would enhance animal comfort and allow for longer continuous operation without frequent recalibration or battery replacement. User interface improvements, such as a touchscreen or mobile application integration, could also simplify device control and data visualization, making the system accessible to a broader range of research laboratories.

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