Ear-Wearable SpO_2 and Heart-Rate Monitoring Device for Low-Ventilation Area Workers

Report submitted to GITAM (Deemed to be University) as a partial fulfillment of the requirements for the award of the Degree of Bachelor of Technology in Electrical Electronics and Communication Engineering

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DECLARATION

We hereby certify that the work presented in this report entitled “**Development of an Ear-Wearable SpO_2 and Heart-Rate Monitoring Device for Low-Ventilation Area Workers**” is the result of original research carried out by the undersigned project team. This report, either in full or in part, has not been submitted previously for the award of any degree or diploma at this or any other institution. All information derived from published or unpublished work of others has been duly acknowledged and referenced. This project has been carried out under the supervision and guidance of **Dr. Kshitij Shakaya.**

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CERTIFICATE

This is to certify that MONISHA HS (Regd. No.: BU22EECE0100439) and PRAJWAL SHETTY (Regd. No.: BU22EECE0100434) has satisfactorily completed Mini Project Entitled in partial fulfillment of the requirements as prescribed by University for VII semester, Bachelor of Technology in “Electrical, Electronics and Communication Engineering” and submitted this report during the academic year 2025-2026.

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Chapter 1: Introduction

1.1 Overview of the problem statement

Workers in low-ventilation environments such as mines, tunnels and sealed industrial facilities are exposed to low oxygen levels and associated health risks. Conventional finger-clip pulse oximeters, although accurate, are impractical for continuous use by mobile workers because they are uncomfortable, restrict movement and are prone to motion artefacts. There is therefore a need for a compact, earwearable device that can continuously monitor SpO_2 and heart rate and reliably distinguish between true hypoxia events and spurious signals.

1.2 Objective

The main objective is to design and prototype an ear-wearable SpO_2 and heart-rate monitoring device for workers in low-ventilation environments, enhanced with machine-learning algorithms to improve reliability and reduce false alarms.

Goals

The specific goals of the project are:

- Integrate a MAX3010x optical sensor into an ergonomic ear-clip housing.
- Acquire and process photoplethysmography (PPG) signals for SpO_2 and heart-rate estimation.
- Apply digital filtering and feature extraction to improve signal quality.
- Train a lightweight machine-learning model to differentiate genuine events from noise.
- Provide real-time alerts (LED/buzzer) when unsafe SpO_2 levels are detected and Ensure comfort, portability and low power consumption for extended industrial use.

Chapter 2: Literature Review

1. **“Evaluation of a novel ear pulse oximeter (Oxy Frame)” Authors:** Fabian Braun, et al.
   Summary / info: Describes design and validation of an ear-mounted pulse oximeter; reports accuracy (RMS error), test protocol on volunteers, and practical design issues for ear sensors (light coupling, motion). Very useful for understanding measurement error, evaluation metrics, and ear sensor placement.
   Why relevant: Directly demonstrates ear-based SpO_2 feasibility and gives benchmark metrics you can compare to.
   Source: Sensors (MDPI).

2. **“Wearable in-ear pulse oximetry validly measures oxygen saturation between 70% and 100%: A prospective agreement study”**
   Authors: C. A. Bubb, M. Weber, S. Schmid, et al. (2023)
   Summary / info: Prospective study validating an in-ear wearable against reference oximeters; includes clinical agreement statistics and practical limitations. Confirms ear devices can be accurate across a wide SpO_2 range. **Why relevant:** Clinical validation evidence — handy for the “motivation / justification” and for setting accuracy targets.
   Source: Digital Health / PubMed.

3. **“Accurate detection of heart rate using in-ear photoplethysmography in a clinical setting”**
   Authors: T. Adams et al. (2022)
   Summary / info: Compares in-ear PPG against ECG during realistic clinical tasks; discusses SNR, artifact handling, and in-ear placement stability.
   Includes processing methods that improve heart-rate extraction. **Why relevant:** Gives concrete signal-processing methods for heart-rate extraction from ear PPG — transferable to SpO_2 pipeline. **Source:** PubMed Central (open access).

4. **“Ear Set: A multi-modal dataset for studying the impact of movement and device placement on ear-PPG”**
   Authors: A. Montanari, et al. (2023)
   Summary / info: Provides a curated dataset and analysis of ear PPG with simultaneous motion/annotations — useful to study motion artifacts and algorithm robustness.
   Why relevant: Real dataset you can use for ML experiments or to compare features and artifact types.
   Source: Nature Scientific Data (dataset paper).

5. **“Photoplethysmography signal processing and synthesis”** (chapter / review)
Authors: Peter H. Charlton / collaborators (comprehensive chapter) **Summary / info:** In-depth review of PPG fundamentals, filtering, AC/DC separation, feature extraction, and methods for synthesizing PPG signals.
Great reference for building preprocessing pipelines.
Why relevant: Foundational reading for every step of your signal chain (filter design, beat detection, perfusion index).
**Source / PDF available online.

6. **“SPECMAR: Fast heart-rate estimation from PPG using modified spectral subtraction with composite motion artifact reference”**
Authors: M. Islam et al. (2018)
Summary / info: Motion-artifact robust heart-rate estimation algorithm using spectral subtraction; demonstrates improved HR extraction during movement.
Why relevant: Offers a concrete artifact-removal algorithm you can adapt for ear PPG preprocessing before SpO_2 estimation. **Source:** arXiv / preprint.

7. **“PPG motion-artifact removal using generative models (CycleGAN)” Authors:** Zargari et al. (2021)
Summary / info: Uses CycleGAN (a generative adversarial technique) to transform noisy PPG into cleaner PPG without requiring accelerometer data.
Shows promise where accelerometer may be noisy or unavailable. **Why relevant:** Advanced technique for artifact reduction if you want to experiment beyond classical filters/regressors.
Source: arXiv / preprint.

8. **“A review of deep-learning methods for photoplethysmography data” Authors:** Guangkun Nie, Jiabao Zhu, et al. (2024)
Summary / info: Comprehensive survey of deep learning applications applied to PPG (SpO_2 prediction, HR estimation, signal quality classification, respiration/HRV tasks). Summarizes datasets, model types, common pitfalls (data scarcity, generalization).
Why relevant: Excellent roadmap of the ML methods you can try and pitfalls to avoid (overfitting, domain shift).
Source: arXiv (open access).

Chapter 3: Strategic Analysis and Problem Definition

3.1 SWOT Analysis

Strengths

- Ear location gives stable PPG signals with faster response to oxygen changes.
- MAX3010x sensor is compact, low-cost and low-power.
- Machine-learning integration reduces false alarms and improves reliability.
- Non-intrusive, comfortable design suitable for continuous monitoring.

Weaknesses

- Prototype still under development.
- Requires sufficient labelled data for ML training.
- Accuracy may be affected in extreme conditions (sweat, temperature).

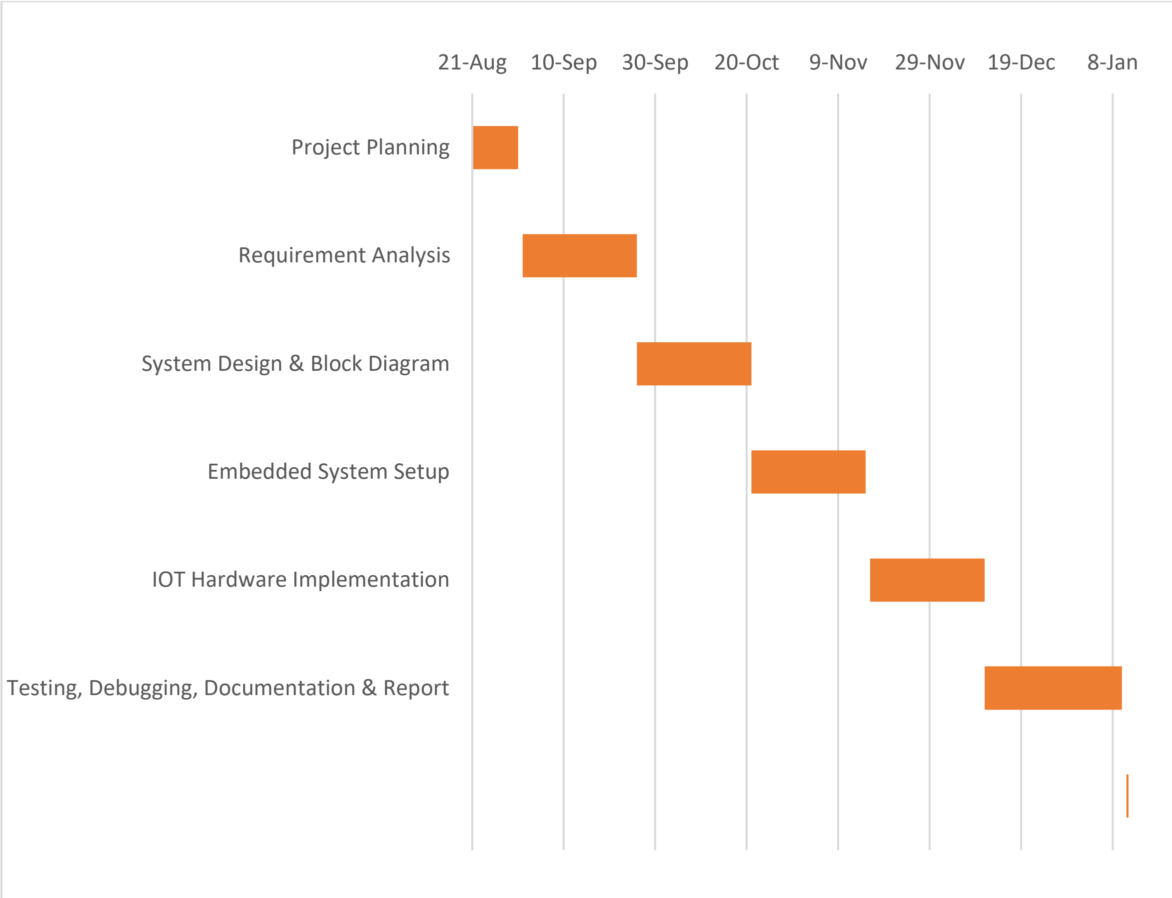
Opportunities

- Increasing demand for worker safety devices in mining, tunnelling, aerospace and healthcare.
- Potential for integration with IoT/cloud dashboards and predictive analytics.
- Expandable to monitor additional vital signs (temperature, respiration).

Threats

- Competition from established commercial wearable manufacturers.
- Rapid technology changes may make chosen components obsolete.
- Regulatory approval requirements for health devices may delay deployment

3.2 Project Plan - GANTT Chart



3.3 Problem statement

Latency and Processing Bottlenecks Conventional health monitoring systems typically rely on microcontroller-based architectures that process instructions sequentially. In critical care scenarios, this serial processing can introduce latency when simultaneously acquiring raw sensor data, filtering noise, and executing diagnostic algorithms. There is a critical need for a system capable of parallel processing to ensure real-time responsiveness and immediate alert generation without the delays inherent in software-based approaches.

Fragmentation of Patient Data Currently, there is a disconnect between real-time vital sign monitoring and the management of patient medical history. Clinicians often lack a unified platform that can display live physiological metrics—such as temperature and heart rate—alongside historical records of surgeries, treatments, and past test results. This fragmentation hinders the ability to make comprehensive, datadriven diagnostic decisions quickly.

Precision and Integration Challenges Standard embedded monitoring solutions often compromise on data precision due to low-resolution internal analog-to-digital converters. To achieve medical-grade reliability, the system must integrate highprecision external components, such as 16-bit ADCs, directly with high-speed hardware logic. The challenge lies in creating a seamless interface that handles this high-fidelity data acquisition while maintaining the throughput required for continuous, error-free monitoring.

Chapter 4: Methodology

4.1 Description of the approach

The proposed system combines a low-cost optical sensor with a microcontroller and a machine-learning pipeline to deliver reliable SpO_2 and heart-rate measurements from the ear.

The overall workflow is as follows:

- **Sensor Integration:** A MAX3010x (MAX30100/MAX30102) pulse-oximeter module will be mounted in an ergonomically designed ear-clip housing. This location is chosen because the ear lobe has good blood perfusion and is less affected by hand movement, leading to more stable photoplethysmography (PPG) signals.
- **Signal Acquisition:** The microcontroller (Arduino Nano or ESP32) continuously samples raw red and infrared light absorption values from the MAX3010x sensor.
- **Pre-processing:** Digital filters (moving average, low-pass Butterworth, baseline wander removal) are applied to remove ambient light interference and motion artefacts.
- **Feature Extraction:** From the cleaned PPG waveform, features such as AC/DC ratios, peak intervals, amplitude variability, and heart-rate variability are computed.
- **Machine-Learning Classification:** Using Python/scikit-learn, a model is trained on labelled data (normal readings vs. true lowoxygen events vs. noise) to distinguish genuine hypoxia from false alarms caused by movement or poor contact.
- **Alert Generation:** When the ML model detects a verified low SpO_2 event, the microcontroller activates visual (LED) and/or acoustic (buzzer) indicators for immediate warning. Optionally, the data are transmitted wirelessly to a supervisor's dashboard.
- **Validation:** The device's outputs will be compared with a reference pulse oximeter under different conditions (rest, mild motion, simulated low oxygen) to assess accuracy and false-alarm rate.This staged approach allows iterative development: first, signal acquisition and basic thresholding; second, ML model training with stored data; third, real-time embedded classification.

4.2 Tools and techniques utilized

Hardware Components:

- MAX3010x optical pulse-oximeter sensor module.
- Arduino Nano / ESP32 development board for data acquisition and processing.
- Ear-clip housing for sensor placement.
- Buzzer and LED indicators for alerts.
- Optional Bluetooth or Wi-Fi module for wireless transmission.

Software & Programming Tools:

- **Arduino IDE** – programming the microcontroller to read sensor data and trigger alerts.
- **Python** – for offline data analysis and machine-learning model development.
- **Libraries:**

NumPy and Pandas for data manipulation.
Matplotlib for visualization of PPG waveforms.
SciPy for digital filter design.
Scikit-learn for training and evaluating ML classifiers. Jupyter Notebook for experimentation.

- **Signal Processing Techniques:**

Low-pass and high-pass filtering to remove noise and baseline drift.
Peak detection algorithms for heart-rate calculation.
Calculation of AC/DC ratio of red/IR signals for SpO_2 estimation.

- **Machine-Learning Techniques:**

Logistic Regression, Random Forest or Support Vector Machine for binary classification (true vs. false event).
Cross-validation to assess model robustness.
Model export to lightweight format for embedded use.

4.3 Design considerations

- **Sensor Placement and Ergonomics:** The ear-clip must be lightweight, non-obtrusive and adjustable to different ear sizes to ensure comfort during long shifts and good optical coupling with skin.
- **Power Consumption:** The device should use low-power modes of the MAX3010x and microcontroller to enable extended operation on a small battery.
- **Sampling Rate and Memory:** A balance between high enough sampling frequency for accurate SpO_2 estimation and low enough data rate to conserve power and storage.
- **Motion Artefact Robustness:** Inclusion of filtering and ML-based artefact detection to maintain accuracy during worker movement.
- **User Safety and Alerting:** The alert system (LED/buzzer) must be clearly perceivable in noisy environments and not cause discomfort.
- **Scalability and Connectivity:** Provision for adding wireless transmission (Bluetooth Low Energy / Wi-Fi) so that supervisors can monitor multiple workers simultaneously on a dashboard.
- **Cost and Manufacturability:** Selection of components that are affordable and widely available for ease of prototyping and scaling up.

Chapter 5: Implementation

5.1 Description of how the project was executed

- **Literature Review & Redefining the Project:**
  A detailed survey of SpO_2/heart-rate sensing systems was carried out, after which the project direction was revised to first build a water-flow–based simulation setup for safe sensor testing.
- **Component Selection and System Design:**
  Hardware components including Arduino Uno, water-flow sensor, float sensor, relay module, and water pump were selected, and a basic block diagram was prepared to plan the system.
- **Hardware Setup & Wiring:**
  The sensors, relay, and pump were assembled and connected to the Arduino. The float sensor was placed in the tank for level detection, and the flow sensor was installed in the pipeline for flow reading.
- **Arduino Programming:**
  Code was written in Arduino IDE to read sensor inputs and automatically switch the pump ON/OFF using the relay based on water level and flow conditions.
- **Testing & Calibration:**
  The system was tested under different flow conditions by adjusting water height and tube diameter. Relay switching, pump performance, and sensor readings were verified for stability.
- **Validation of Simulation System:**
  Long-duration tests confirmed that the system produced stable, repeatable flow patterns suitable for future testing of SpO_2 and heart-rate sensors.

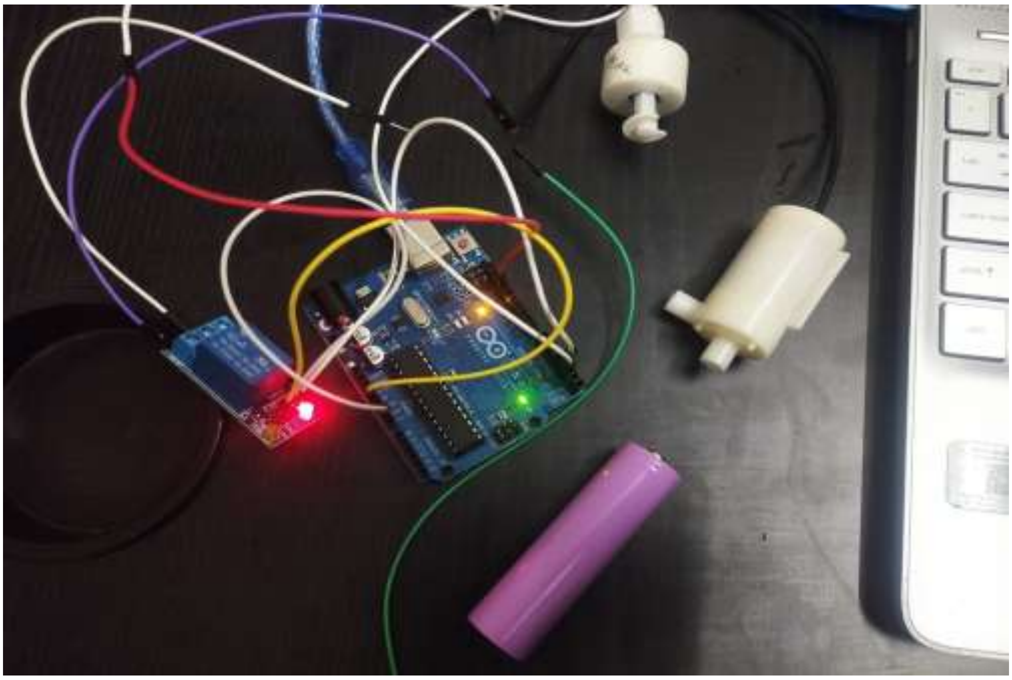
5.2 Challenges faced and solutions implemented

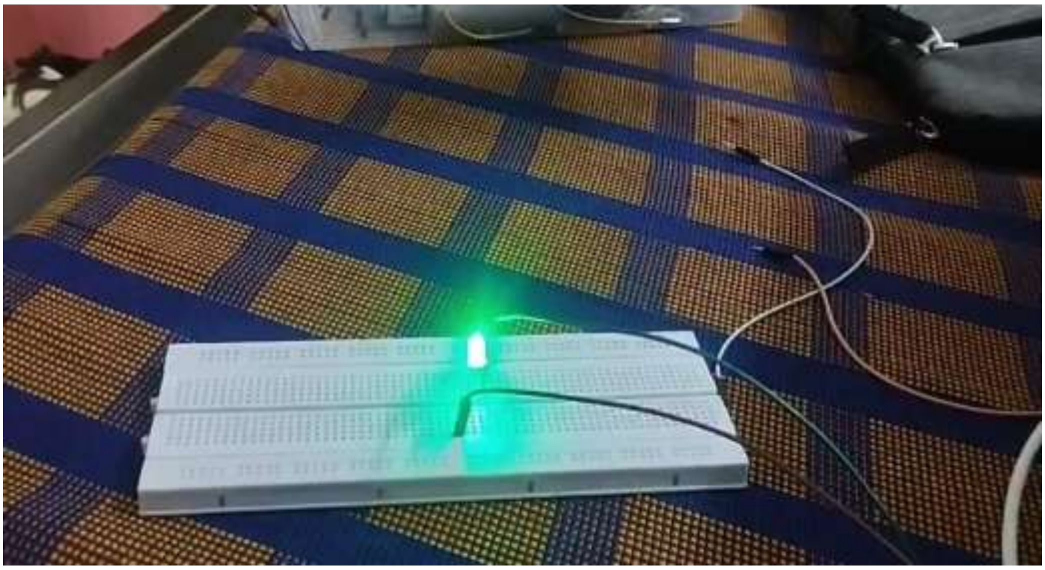
- **Unstable Water Flow:**
  Challenge: Initial flow was inconsistent due to air bubbles and uneven pipe height.
  Solution: Adjusted pipe positioning and ensured proper sealing to maintain smooth, continuous flow.
- **Float Sensor False Triggering:**
  Challenge: Float sensor produced noisy or fluctuating signals.
  Solution: Added software debouncing and tested sensor hysteresis to ensure stable pump ON/OFF switching.
- **Relay Switching Issues:**
  Challenge: Relay switched with delay or occasional misfires during pump load.
  Solution: Verified wiring, used a proper transistor-driven relay module, and stabilized power supply.
- **Pump Voltage Drop:**
  Challenge: Pump performance dropped when powered through unstable connections.
  Solution: Used a 3.7V Li-ion battery with regulated power to ensure consistent motor operation.
- **Leakage and Loose Connections:**
  Challenge: Minor water leakage occurred at joints affecting flow readings.
  Solution: Tightened pipe fittings and applied waterproof sealing to avoid pressure loss.
- **Inaccurate Flow Readings:**
  Challenge: Initial flow sensor readings were not steady during testing.
  Solution: Performed calibration, cleaned the sensor wheel, and aligned the sensor orientation for accurate measurement.

Chapter 6: Results

6.1 Outcomes

- Successfully developed a **hardware-based flow simulation system** using Arduino, sensors, and pump.
- Achieved **stable and continuous water-flow**, suitable for replicating blood-flow patterns for sensor testing.
- Float sensor accurately controlled pump ON/OFF states to maintain water availability.
- Water-flow sensor generated usable flow-rate data for comparison with future PPG sensor behavior.
- Relay switching was verified to be **accurate and noise-free**, ensuring reliable pump control.
- Overall system behaved consistently during long-duration testing, validating its use as a laboratory simulation tool.





Project Demonstration - Video Link

6.2 Interpretation of results

The results indicate that the system can:

- Produce consistent flow variation patterns similar to physiological pulses
- Respond correctly to changes in water level
- Maintain stable flow without turbulence when parameters are tuned
- Provide repeatable flow data necessary for validating SpO_2/PPG sensors
- This confirms that the simulation rig is effective for early-stage evaluation of wearable SpO_2 sensors without relying on human volunteers.

6.3 Comparison with existing literature or technologies

- Existing SpO_2 testing setups use **biological subjects**, which are inconsistent and raise safety concerns.
- Commercial simulators are expensive and not customizable.
- The proposed system offers a **low-cost, safe, highly repeatable alternative** for controlled experimentation.
- No commercial system currently provides a simple **water-flow–based physiological simulation**, making this approach unique and valuable for academic prototyping.

Chapter 7: Conclusion

The Review-2 phase marks a major advancement from theory to practical implementation.

The complete water-flow simulation platform has been designed, constructed, and tested successfully. The system is capable of generating stable, repeatable flow patterns that resemble physiological blood flow. These patterns are essential for testing the behavior of SpO_2 and heart-rate sensors under controlled conditions.

The results validate the feasibility of using this simulation setup as a preliminary testing environment before integrating actual SpO_2 sensors or deploying wearable prototypes. The system is reliable, safe, and effective for studying how sensors respond to different flow conditions like low flow, no flow, and sudden flow variations.

This forms a strong foundation for the next stages of the project—actual biomedical sensor integration and wearable device development.

Chapter 8: Future Scope

1. Integration of Real Sensors
    - Connect MAX30102 / MAX30105 SpO_2 sensors to flow setup.
    - Compare simulated flow signals with actual PPG waveforms.

2. Flow-to-PPG Pattern Mapping
    - Evaluate how low-flow affects SpO_2 readings.
    - Identify threshold flow levels corresponding to hypoxia-like conditions.

3. Enhance Flow Simulation Accuracy
    - Add pulse-generating mechanisms (valves/solenoid-based).
    - Improve analog resemblance to biological pulsatile flow.

4. Wireless Monitoring Upgrade
    - Integrate Node MCU/ESP32 for real-time remote monitoring.
    - Enable cloud or mobile-based observation dashboard.

5. Long-Duration Performance Testing
    - Test pump endurance for 4–8hour continuous operation.
    - Evaluate battery drain, heat generation, and mechanical reliability.

6. Transition Toward Wearable Device Development
    - Begin integrating ear-wearable SpO_2 sensors.
    - Analyze data from controlled simulation to design real-user tests.
    - Prepare ergonomic ear-clip hardware.

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