MAYO CLINIC

A Scoping Review on Smart Bandages with Gas Monitoring Capabilities and a Proposed Machine Learning Protocol for On-Device Wound Monitoring

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INTRODUCTION

- The integration of the Internet of Things (IoT) into wound care offers revolutionized management of wounds by enabling real-time diagnostic insights and treatment capabilities not previously possible in traditional dressings.
- This scoping review explores the impact of gas-detecting smart bandages, specifically those sensing pulse oxygen saturation (SpO2) and tissue oxygenation (pO2), and their potential to improve patient outcomes. As part of this review, we propose a closed-loop, cloud-based protocol for continually fine-tuning predictive models meant to run locally (on-device) via leveraging device IoT capabilities.

METHODS

Three electronic databases were searched for current research on smart bandages with gas monitoring capabilities

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Studies within the last 10 years focused on at-home wound monitoring were included, while non-human studies and studies focusing on traditional wound care or smart bandages were excluded.

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Studies focusing on gas-detecting smart bandages were included and data was extracted for the review

RESULTS

Table 1: Devices with a Gas Monitoring Ability

Biomarker	Linear Range (Sensitivity)	Features	Limitations	Reference
Pulse Oxygen Saturation	SpO_2: 70-100% (±2%)	Good stretchability (35% strain), continuous multi-parametric sensing.	Trade-offs in LED current (PPG signal accuracy)/power usage.	Wang et al., 2019
Oxygen	0.6-7% O_2 (1.5 μA/% O_2)	Flexible, sensitive, modular sensor replacement.	Environmental oxygen interference, requires calibration for environment.	Mostafalu et al., 2015
Tissue oxygenation	0-160mmHg pO_2 [@ 36ºC] (NS)	Non-invasive, continuous monitoring, machine-learning enhanced accuracy.	Temperature impacts accuracy, external factors can disrupt sensing.	Wittheuer et al., 2021
Pulse Oxygen Saturation	70-100% (Average error ~2.6%)	Low power consumption, real-time monitoring.	Limited by the sensor's ability to measure oxygenation in poor perfusion conditions.	Panahi et al., 2023
Oxygen	SpO_2: 0-30% O_2 (1.5 μA/% O_2)	Flexible, sensitive, on-demand drug delivery.	Drift, environmental oxygen interference, requires calibration for environment	Punjiya et al., 2017
Pulse Oxygen Saturation	70-100%	Real-time monitoring, decision support enhanced via machine learning model.	Need for regular calibration, system performance depends on training dataset.	Sattar et al., 2019

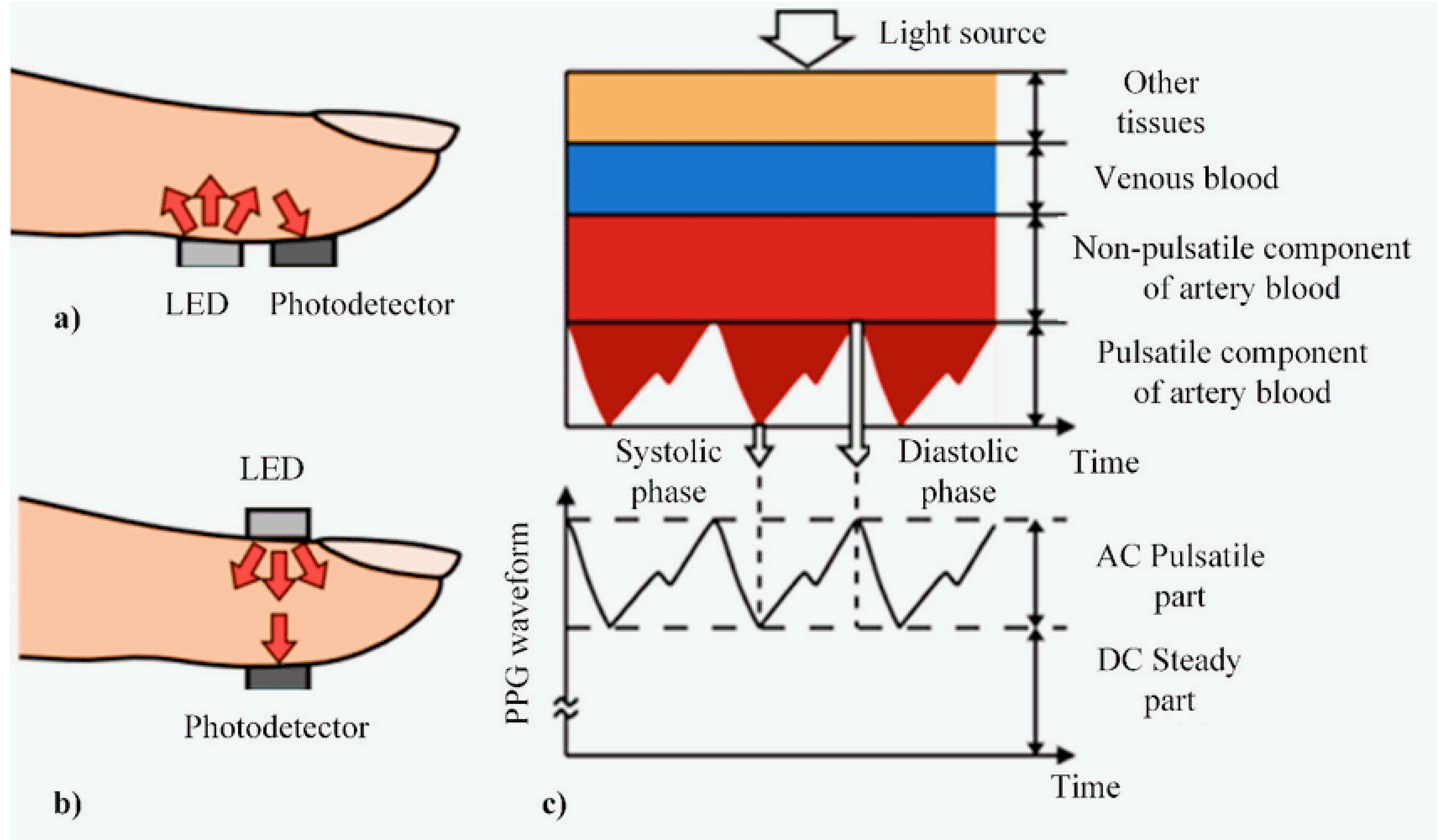

Figure 1. Photoplethysmography (PPG), a technique used to measure blood flow and oxygen saturation. Panels (a) and (b) depict two PPG sensor configurations: transmissive mode, where light passes through the tissue to a photodetector, and reflective mode, where light is reflected to a detector on the same side. The middle diagram shows how light interacts with different tissue layers, with the pulsatile arterial blood component contributing to the AC signal, while venous blood and other tissues form the steady DC component. Panel (c) presents the PPG waveform, which reflects blood volume changes during the cardiac cycle. This technology is particularly relevant for smart wound monitors, which use reflective PPG to assess tissue oxygenation and detect hypoxia, aiding in wound healing assessment

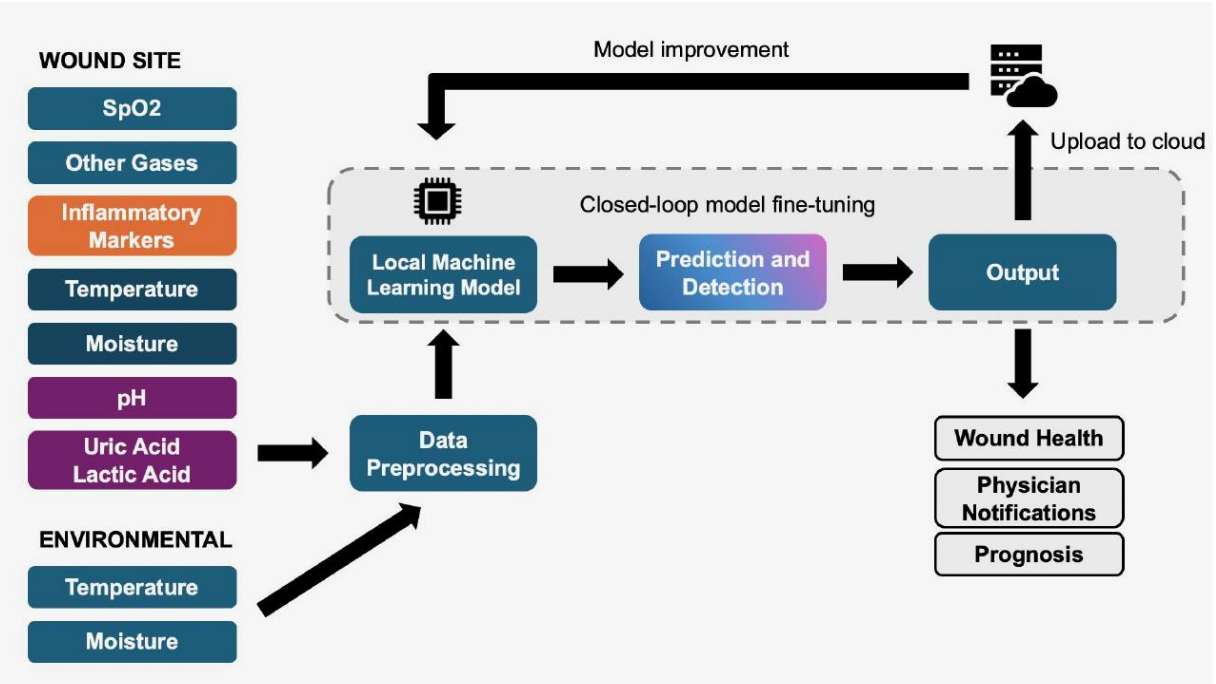

Figure 2. A protocol for smart wound monitoring where device-level diagnostic predictions are continuously refined through provider validation. Key wound site parameters and environmental factors are collected and preprocessed before being fed into a machine learning model. The model performs real-time prediction and detection of wound health status, with outputs such as wound health assessments. Data is uploaded to the cloud for further analysis, enabling model fine-tuning based on provider feedback.

Table 2: Pros and Cons for Monitoring SpO2 and pO2

Monitoring SpO2:

Pros	Cons
• Non-invasive, easy to monitor with wearable technology • Low susceptibility to calibration issues • Provides real-time feedback on systemic oxygen delivery	• May not accurately reflect localized oxygenation • Insufficient for determining tissue-specific oxygen deficits • Influenced by motion artifacts, peripheral perfusion, and other factors

Monitoring pO2:

Pros	Cons
• Provides a localized measurement of oxygen at wound site • Excellent for assessing wound healing in chronic wounds	• Requires more invasive sensors and proximity, which complicates usability • Electrochemical sensors may require frequent calibration due to drift

DISCUSSION

- SpO2 methods offer non-invasive and validated systematic feedback, while pO2 methods enable localized intervention.
- Inadequate oxygen delivery is an important marker of impaired healing, and measuring tissue oxygenation and pulse oxygen saturation is critical for assessing repair progress and the efficaciousness of wound healing interventions.
- The integration of machine learning—particularly in the form of small models that can run on-device could enhance these systems by enabling real-time diagnostic alerts and modulating potential device therapeutic capabilities, thus improving wound management and outcomes.
- We propose a closed-loop, cloud-based protocol for smart wound monitoring where device-level diagnostic predictions are validated through provider input to continually fine-tune the device's diagnostic model and improve model accuracy at an individualized level.

CONCLUSIONS

- The gas-monitoring capabilities of smart bandages have shown promise in enhancing wound care through real-time physiological insights.
- Integrating machine learning into smart wound monitoring devices can enhance real-time diagnostics and potentially modulate therapeutic interventions.

REFERENCES

Wang C, Pan C, Wang Z. Electronic Skin for Closed-Loop Systems. ACS Nano. 2019 Nov 26;13(11):12287-12293. doi: 10.1021/acsnano.9b06576. Epub 2019 Oct 18. PMID: 31626533.

Mostafalu P, Tamayol A, Rahimi R, Ochoa M, Khalilpour A, Kiaee G, Yazdi IK, Bagherifard S, Dokmeci MR, Ziaie B, Sonkusale SR, Khademhosseini A. Smart Bandage for Monitoring and Treatment of Chronic Wounds. Small. 2018 Jul 6:e1703509. doi: 10.1002/smll.201703509. Epub ahead of print. PMID: 29978547.

Witthauer L, Cascales JP, Roussakis E, Li X, Goss A, Chen Y, Evans CL. Portable Oxygen-Sensing Device for the Improved Assessment of Compartment Syndrome and other Hypoxia-Related Conditions. ACS Sens. 2021 Jan 22;6(1):43-53. doi: 10.1021/acssensors.0c01686. Epub 2020 Dec 16. PMID: 33325684.

Panahi N, Hashemnia M, Rezaei F, Cheraghi H. Effect of Piascledine-bacterial nanocellulose combination on experimental cutaneous wound healing in rat: Histopathological, biochemical and molecular studies. Int Wound J. 2023 Oct 1;21(2):e14418. doi: 10.1111/iwj.14418. Epub ahead of print. PMID: 37779106; PMCID: PMC10825074.

Punjiya, M., Nejad, H.R., Mathews, J. et al. A flow through device for simultaneous dielectrophoretic cell trapping and AC electroporation. Sci Rep 9, 11988 (2019). https://doi.org/10.1038/s41598-019-48198-x

Sattar, Hina, Bajwa, Imran Sarwar, ul Amin, Riaz, Muhammad, Jan, Mushtaq, Muhammad Faheem, Kazmi, Rafaqut, Akram, Muhammad, Ashraf, Muhammad, Shafi, Umar, Smart Wound Hydration Monitoring Using Biosensors and Fuzzy Inference System, Wireless Communications and Mobile Computing, 2019, 8059629, 15 pages, 2019. https://doi.org/10.1155/2019/8059629