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AI Powered Platform: Microbiome-Driven Cardiovascular Diagnostics Via Smart Microneedle Patch Integration

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Abstract: ***Cardiovascular disease is a leading global cause of mortality, yet traditional diagnostic tools often overlook the gut microbiome's role in disease progression. This study introduces an AI-powered microneedle patch that detects microbiome-related biomarkers, offering a noninvasive diagnostic approach for early-stage cardiovascular conditions. The patch, coated with specific antibodies, initiates redox reactions upon detecting microbial proteins, producing measurable signals for real-time analysis. Complemented by a machine learning-based web system trained on symptom-disease associations, the platform allows for dual-mode diagnostics using user-reported inputs and biosensor data. Designed with accessibility in mind, especially for underserved areas, this platform presents a novel convergence of artificial intelligence, biosensing, and microbiome science for personalized cardiovascular risk assessment. Despite growing evidence linking microbial bacterial, viral, and fungal infections to cardiovascular conditions, early diagnostic tools remain limited, particularly in underserved regions. To address this gap, we developed a noninvasive, AI-powered microneedle patch that detects microbiome-related biomarkers in blood. Coated with antibodies specific to disease-associated microbial proteins and metabolites, the patch initiates redox reactions to generate measurable signals for real-time analysis. Complementing the patch, we designed a machine learning-based online platform that leverages biosensor data and user-reported symptoms to provide rapid disease identification and cardiovascular risk assessment. Built using a neural network trained on synthetic symptom-disease mappings via TensorFlow/Keras, the model outputs the most likely diagnosis with a probability score. This dual-mode diagnostic platform, combining biosensing with artificial intelligence which offers a novel and accessible solution for personalized cardiovascular care, particularly benefiting under-resourced populations.***

Keywords: Microbiome Diagnostics, Microneedle Patch, Cardiovascular Disease, Artificial Intelligence, Noninvasive Biosensors

1. Introduction

Cardiovascular disease remains the leading global cause of death, and the disease is responsible for nearly one-third of all mortality on earth (NSC, 2023). Some current diagnostics for cardiovascular diseases primarily focus on physiological factors such as heart rate, blood pressure, and cholesterol levels and they rarely consider a vital component of cardiovascular health: the gut microbiome (Tang, 2018). A majority of the recent studies support a causal connection between infections caused by bacteria, viruses, and fungi in the microbiome and the beginning of cardiovascular disease. However, there are very few diagnostic measures that exist for the detection of these microbiome-associated biomarkers at an early stage (Heidt, 2020). This leaves behind a gap leading to late diagnosis, enhanced cost of treatment, and eventually leads to increased mortality.

Table 1: Number of deaths caused by heart disease by race. (Source: CDC, 2025)

Race or Ethnic Group	% of Deaths
American Indian or Alaska Native	15.5
Asian	18.6
Black (Non-Hispanic)	22.6
Native Hawaiian or Other Pacific Islander	18.3
White (Non-Hispanic)	18.0
Hispanic	11.9
All	17.4

The data in Figure 1 shows how heart disease deaths are much higher in certain racial groups, especially among Black (Non-Hispanic individuals as compared to Whites (Non-Hispanic) (CDC, 2025). Asians and Native Hawaiians, or other Pacific Islanders, also have a slightly higher death rate. This higher mortality rate can be linked to the lack of early diagnostic tools in underserved communities. The shortage of trained healthcare workers in these areas makes the problem even worse, leading to later detection, higher treatment costs, and more deaths, as reflected in the chart (McNeill, 2022).

To overcome these disparities, we introduce a novel and noninvasive microneedle patch that is capable of detecting microbiome-associated biomarkers in the bloodstream. It is made of biocompatible substances such as silicon, polymers, or hydrogels. The patch is made such that it melts when it comes into contact with the stratum corneum of the skin. The microneedles are coated with antibodies and enzyme-linked detection molecules that bind to disease-specific proteins and antigens. Upon binding, a redox reaction occurs, producing a measurable electrochemical signal that allows real-time detection of heart disease-related microbial activity. This represents a major advancement over current wearable diagnostics, which rarely consider microbiome-derived indicators. By directly targeting bacterial, viral, and fungal biomarkers, our patch fills a critical gap in cardiovascular diagnostics.

Along with the patch, we developed an AI-powered online system that enhances diagnostic precision. It uses a neural network model built with TensorFlow/Keras, and the system predicts potential diseases based on the user-inputted symptoms. It is trained on a synthetic dataset. The model uses dense layers with ReLU activation to identify patterns in binary symptom data and applies a softmax layer to predict the probabilities of different heart diseases.

This study is important because it provides an integrated diagnostic method that effectively identifies both a biological gap and a systematic gap in cardiovascular care. Traditional methods are typically limited by macroscopic measures of physiology, such as blood pressure, heart rate and cholesterol. Impactful measures of the underlying microbial dynamics, based on an increasing number of causative alliances to cardiovascular disease—are not accounted for. Using a microneedle patch system allows for continuous and non-invasive real-time assessment of microbiome-associated biomarkers (such as bacterial, viral, fungal proteins, etc.) in the circulation. This method allows for new sets of wearable diagnostic signals that otherwise wouldn't be monitored for early disease pathophysiology.

Beyond just augmenting biomedical precision, our solution advances healthcare equity. Coupling the patch with an artificial intelligence-enabled, user-centered diagnostic front end allows for patients, even those from marginalized or rural settings, to fairly and readily adopt these low-cost and accessible screening practices. These underserved populations typically see an abrupt cardiovascular mortality, due to disturbances in diagnosis and finding clinical specialists to arrive at alternatives to care. Our diagnostic holistic approach reduced this gap and improves early interventions, personalized treatment, access to specialists, and reduced treatment costs with improved outcomes.

The proposed platform has even more far-reaching implications for future predictive and preventive medicine. With biosensing and machine learning capabilities, it serves as a prototype for decentralized, data-driven healthcare. It allows real-time symptom input and biomarker monitoring, which contribute to larger epidemiological tracking and individualized risk assessments. These two distinct roles greatly improve accuracy around CSU diagnostics and adds to the precision medicine field, elevating care through awareness of patient biological and environmental differences.

Overall, this study offers a superior solution that gracefully combines pioneering bioengineering, artificial intelligence, and health equity. It is positioned to transform cardiovascular diagnostics, address previously obscured microbial subtlety driving cardiovascular disease, widen access to care, and implement initiatives that can shape global health in an effort to decrease cardiovascular mortality, especially among populations who face the greatest inequities.

This study is significant because it proposes a novel diagnostic system that not only bridges existing technological gaps in cardiovascular diagnostics but also expands access to early detection methods in resource limited settings. This tool allows for flexible use across different healthcare settings and allows individuals to determine the disease from the comfort of their own home. Ultimately, this project aims to bridge the gap between early disease detection and underserved populations. It transforms global diagnostic practices and saves lives through microbiome-focused cardiovascular monitoring.

The purpose of this study is to design and evaluate a noninvasive, AI-integrated microneedle patch capable of detecting microbiome-derived cardiovascular biomarkers, particularly to address diagnostic gaps in underserved communities.

2. Literature Review

2.1 Background of the Gut-Heart Axis

The gut-heart axis refers to the interconnected relationship between the gut microbiome and cardiovascular health. In recent years, a growing body of scientific evidence has shown that gut microbiota, consisting of trillions of microorganisms in the gastrointestinal tract, is essential for many systemic processes, and beyond digestion includes: inflammation, lipid metabolism, and immune signaling (Liu et al., 2021). This relationship has major and widespread applications in cardiovascular disease (CVD), one of the biggest public health issues in the world.

One mechanism through which the gut can confer effects on heart health is through microbial metabolites.

The leading microbial metabolite documented in the literature is trimethylamine N-oxide (TMAO), a compound generated from the microbiome's metabolism of dietary components with choline and carnitine (e.g., red meat and eggs). TMAO can put patients at increased risk for atherosclerosis, endothelial dysfunction, and major adverse cardiovascular events. On the other end of the spectrum are the beneficial short-chain fatty acids (SCFAs) from dietary fiber fermentation in the gut, which can exert anti-inflammatory benefits and appear to protect against hypertension and vascular inflammation.

Imports in our gut microbiota balance, which are termed dysbiosis, can be viewed as an offending risk factor to gut health (and beyond). For example, with dysbiosis comes excess intestinal permeability, translocating inflammatory mediators into circulation, hence putting the cardiovascular system at higher risk. Subsequently, diet, antibiotics, stress, and physical inactivity can put gut microbiota at a higher risk for imbalance, especially by populations already at risk for CVD pathologies.

Although the gut-heart axis is a salient process, it is not yet implemented in clinical diagnostics. Most cardiovascular diagnostic assessments neglect the contributions of microbes to cardiovascular health. However, a new technology to conduct point-of-care and real-time monitoring for microbiome-derived biomarkers could lead to potential advancements in diagnostic and preventive strategies for heart disease. Ultimately, the gut-heart axis provides opportunities for further understanding and utilizing cardiovascular health in an individualized and holistic methodology.

The Human Microbiome

The human microbiome is a vast and complex community of microorganisms, including bacteria, archaea, viruses, and microbial eukaryotes that live in and on the human body (Ogunrinola, 2020). These microbes play an essential role in maintaining overall health by supporting immune function, aiding digestion, and helping to regulate inflammation. Most

of the bacterial population falls into two major groups called the Bacteroidetes and Firmicutes (Johnson, 2016).

Microbiome Physiology

Physiologically, the microbiome is integrated into several host systems. Dysbiosis, or disruptions in gut microbiota, has been reported to influence complete blood count parameters. Elevated white blood cell counts can be a sign of inflammatory responses resulting from microbial derangements (Schluter, 2021). On the other hand, impaired red blood cell production can be indicative of altered erythropoiesis influenced by gut bacteria. Moreover, microbial metabolites such as short-chain fatty acids (also known as SCFAs) can modulate platelet function and systemic inflammation. These interactions provide strong diagnostic clues and show the microbiome's broader physiological role beyond digestion, making it a valuable focus in early disease detection and risk assessment (Yan, 2023).

Microbial Interactions and Complexity

What makes the microbiome particularly fascinating is not just its diversity but the way these organisms interact. Some form cooperative relationships, others compete for resources, & many exist independently within this intricate ecosystem. Many controversies still exist regarding the exact components of the microbiome, particularly whether extracellular DNA, plasmids, and mobile genetic elements should be part of the definition (Ma, 2024). Viral, fungal populations, and bacteriophages contribute to that complexity, which also shows the microbiome's role as a complex web of interdependent species. The understanding of these microbial populations by techniques like microbial network analysis is now a necessity for the identification of functional relationships and disruptions linked to disease (R. P. Robinson, 2025; Berg, 2020).

Link to Metabolic and Systemic Diseases

For instance, the interaction between gut microbiota and metabolic health is very well established. Alterations in microbial communities can cause obesity and other metabolic disorders through the mechanism of the gut-brain axis, which can affect appetite, etc (Asadi, 2022). Similarly, infections by some microbes, like Aspergillus species, enteroviruses, Helicobacter pylori, and the Hepatitis C virus, have been linked to more systemic illnesses (Singh & Kumar, 2021).

Link to Cardiovascular Health

Cardiovascular disease is still one of the top causes of death worldwide (Di Cesare, 2024). It is usually diagnosed using cholesterol levels, blood pressure, and imaging. But new research is showing that the microbiome also plays a part. Microbial imbalances can affect how fats are processed, how blood vessels work, and how inflammation spreads in the body, all of which are linked to heart disease (Masenga, 2022). Still, microbiome testing for heart risk isn't widely used yet, especially in places where healthcare access is limited.

Real World Use and Research

Our project combines a digital platform powered by AI with a microneedle patch, aiming to make microbiome-based testing more practical and available. We're focused on noninvasive tools that people can actually use, even in areas without easy access to care. It's a step toward bringing microbiome science out of the lab and into real-world healthcare.

2.2 Microneedle Technology

Since its inception in the late 1990s, microneedle technology has come a long way, having been first conceived in 1998 as a painless and minimally invasive method for transdermal drug delivery. In 1998, for example, researchers like Henry et al. had the idea of developing tiny needles that could penetrate through the stratum corneum (the protective layer of skin) without hitting pain receptors. The application of microneedles quickly grew from cosmetics and vaccine delivery to diagnostics and biosensing in real time. Today, microneedles are essential in wearable health technologies, especially for monitoring chronic disease.

For diagnostics, microneedles have been especially useful for sampling interstitial fluid (ISF) as it is typified by many biomarkers that can accurately show systemic physiologic states. Nevertheless, inspecting ISF or detecting blood proteins through the skin involves technical challenges. First, it is difficult to obtain enough volume of ISF, as its flow rate into the microneedles is quite low. Next, since ISF is typically less concentrated than blood, the samples of ISF will require very sensitive detection systems that can recognize clinically meaningful concentrations. After sampling of biomarker-specific fluid is obtained, maintaining stability is also important since metabolites, and particularly microbial proteins, are prone to degradation or oxidation, and often need to be read out in real time. Calibration of the device in the context of the patient's skin properties, including how permeability varies between individuals, and reconciling the choice of materials for biocompatibility, represent ongoing engineering hurdles.

Nonetheless, microneedle glucose sensors that monitor glucose for diabetes management have established a precedent and facilitated the development of a wider spectrum of devices. For example, continuous glucose monitoring (CGM) systems by Gao et al. (2016) have been commercialized with companies like Abbott (FreeStyle Libre) and Dexcom by accumulating glucose levels in interstitial fluid (ISF) over time, using microneedles. These devices have reassured researchers that microneedle-based sensing can be valid and noninvasive, and that users can receive continuous feedback on their health without the discomfort of finger pricks.

Our smart microneedle patch will also improve cardiovascular disease diagnostics through the characterization of microbiome-derived biomarkers in the fluid that it samples, extending the use of microneedles beyond the diagnostic pathways mentioned here. Our patch is coated with antibodies that will bind to microbial proteins and metabolites, and create an electrochemical reaction upon detection, with real-time diagnostics. Our patch improves on the expectations for glucose biosensors by incorporating artificial intelligence-based risk analysis and expanding on the currently uncharted infectious and inflammatory

diagnostic pathways that have not yet been shown as noninvasive. Thus, our technology converges biomedical engineering, artificial intelligence, and microbiome to reduce widespread disparities in access to cardiovascular health.

3. Research Gap

Most current tools for cardiovascular diagnostics rely on general indicators such as heart rate, blood pressure, and cholesterol levels. While useful, these measures often miss early signals of disease and do not account for the role of the gut microbiome in cardiovascular health (Liu et al., 2021). Recent studies have shown that microbial metabolites like trimethylamine N-oxide (TMAO) and short-chain fatty acids (SCFAs) are closely linked to inflammation and plaque formation (Schiattarella et al., 2017; Fernandez-Raudales et al., 2023; Liccardo et al., 2023), yet there are no wearable or non-invasive technologies that monitor these biomarkers in real time.

Popular consumer wearables such as Apple Watch, Fitbit, and Holter monitors focus on tracking physical activity and heart rhythm. However, they are not equipped to detect biochemical changes related to microbial imbalance, which are important for identifying early cardiovascular risk (Hu et al., 2023; Wu et al., 2023). On the other hand, microbiome diagnostics like stool testing or blood-based metabolite panels require lab processing, are not continuous, and often remain inaccessible to people without regular healthcare access (Li et al., 2020).

In addition, most AI-driven health platforms do not integrate biochemical data such as metabolites or microbial markers, focusing instead on generalized physiological metrics like heart rate or symptom checklists. This limitation significantly reduces their ability to generate accurate, personalized risk assessments for conditions where the microbiome plays a central and dynamic role in disease progression, particularly in complex disorders such as cardiovascular disease, metabolic syndrome, and autoimmune conditions (Liu et al., 2021). Incorporating microbiome-derived biomarkers would not only improve diagnostic specificity but also allow for more targeted preventive strategies that are relevant to an individual's biological profile.

Together, these gaps point to a need for a new class of diagnostic technology that can continuously track microbiome-related biomarkers in a non-invasive, accessible format. Bridging this gap could improve early detection and prevention of cardiovascular disease, especially in populations that are currently underserved by traditional diagnostic tools (Hu et al., 2023).

4. Methodology

This project involves the development of a prototype symptom-based disease suggestion system using a Multilayer Perceptron (MLP) neural network built with Python, TensorFlow/Keras, and Scikit-learn. An initial mapping of symptom-disease relationships was used to create a probability matrix reflecting how likely certain symptoms are to appear with specific cardiovascular or microbiome-related conditions. Due to limited access to open-source, symptom-linked clinical datasets in this area, a synthetic dataset was generated based on this matrix. This allowed for early algorithm development and system testing, while acknowledging that real-world clinical data will be essential for future validation.

The synthetic dataset was preprocessed by encoding categorical disease labels using one-hot encoding and splitting the data into training and testing sets. The MLP model included multiple dense layers with rectified linear unit (ReLU) activations and a softmax output layer. The model was compiled using the Adam optimizer and categorical cross-entropy loss, then trained on the synthetic training data. The performance was evaluated on a held-out test set, with accuracy as the main metric. Additional evaluation included basic classification metrics such as precision, recall, F1-score, and a confusion matrix to better understand prediction patterns.

For predictions, user input (binary yes/no responses to symptoms) is converted into a numerical input vector. This vector is passed through the trained model, which outputs probabilities for each disease class. The top two disease suggestions, along with their predicted likelihoods, are presented to the user. The system is structured with modular code and controlled environments to support future updates and integration with validated clinical data sources.

5. Data Analysis

A small, low-power near-field communication (NFC) or Bluetooth chip discreetly integrated into the microcontroller allows the patch to wirelessly connect. As the redox reaction occurs, producing an electrochemical response indicative of the target cardiovascular biomarker, the microcontroller converts this response into a digital readout.

When the target biomarker approaches the set threshold indicative of the target cardiovascular condition, the green LED emitted by the patch emits an intense glow, directed by the system.

To protect the privacy and confidentiality of the data, this information is wirelessly sent to the paired device—be it a computer, tablet, or smartphone via encrypted messages. An artificial intelligence (AI) platform at the receiving device, connected to pre-trained neural network machine-learning models exposed to clinical dataset feeds, painstakingly processes the received data. It carefully cross-checks the detected signals to determine conformity with early markers of cardiovascular risk related to gut microbiota-related biomarkers.

Unobtrusively, the biosensor patch picks up on cardiovascular biomarkers of the microbiome, like trimethylamine N-oxide (TMAO) or short-chain fatty acids (SCFAs), present in the interstitial fluid resting close to the surface of the skin. As the microneedle patch is applied to the skin, the microneedles softly pierce the epidermis to reach the fluid lying beneath the skin surface. Tips of the microneedles are functionalized with biorecognition

molecules such as enzyme-linked receptors, DNA aptamers, or expressed antibody fragments, each painstakingly designed to interact specifically with the target metabolite. Upon contact, a redox (reduction-oxidation) reaction typically occurs, catalyzed by an enzyme or facilitated by an electrochemical mediator at the sensor interface. This redox reaction causes the local electron density to change, generating an electrochemical response, e.g., deviation of current or potential, that is proportional to the biomarker present. This response is harvested and sent to an onboard potentiostat, which is integrated into the patch's MCU, where it filters the signal.

After this, the analog response is converted to the digital domain using an onboard analog-to-digital converter (ADC) integrated into the MCU. After digitization, the microcontroller carefully compares the response to a preprogrammed threshold value, one that corresponds to medically derived levels of raised cardiovascular risk. If the biomarker level exceeds this threshold, the patch is actuated, causing an onboard green light to give an immediate visual indication of abnormal levels. At the same time, the data is sent securely using a platform, such as Bluetooth Low Energy (BLE) or Near-Field Communication (NFC), to a paired mobile phone or computer.

To protect patient privacy, the response is encrypted under cipher protocols upon transmission. At the recipient side, an AI-powered diagnostic software platform decodes the incoming biomarker information. This platform utilizes machine-learning algorithms pre-trained using large clinic-derived and microbiome-derived datasets to interpret the response implications, considering the concentration and time-course trends. It cross-checks the biomarker pattern with early cardiovascular disease precursors based on gut dysbiosis. Depending upon the strength of the response's signature, the platform can produce user-adjustable risk scores, recommend preventive action, or notify healthcare professionals.

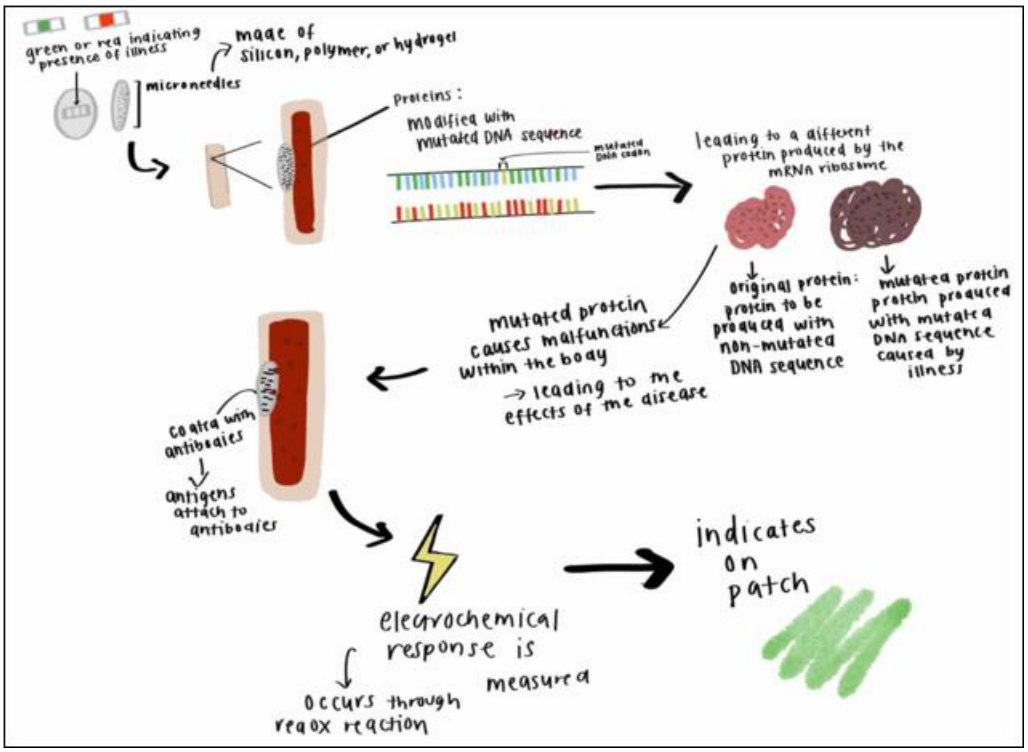

Figure 1: Detailed overview of the microneedle patch and the detection of these mutations that form

This figure depicts the microneedle patch and the detection of the mutations. The microneedle patch is made from safe materials like silicon, polymer, or hydrogel. It has tiny microneedles that painlessly enter the skin and interact with interstitial fluid to detect proteins indicative of underlying disease pathology. Inside the patch, a mutated DNA sequence leads to the production of an altered protein. This mutation changes the amino acid sequence during translation, resulting in a different protein than the one created from normal DNA. These mutated proteins can disrupt normal cellular functions, leading to symptoms of illness. The microneedles are coated with specific antibodies that recognize and bind to these abnormal proteins (antigens). When binding occurs, a redox reaction is triggered, creating an electrochemical signal. This signal is then translated into a visual color change on the patch.

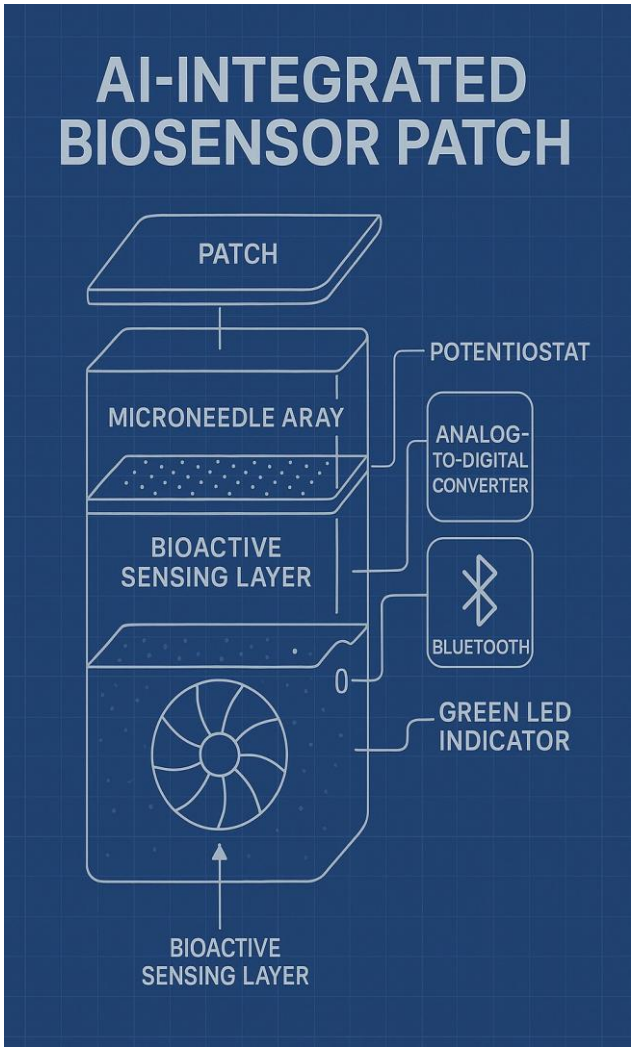

Figure 2. The figure shown displays the inner structure of the AI-powered biosensor patch. This device consists of a dermal adhesive layer comprising a functionalized array of microneedles for the detection of biomarkers associated with the microbiome. Upon binding of these biomarkers, a redox reaction occurs in the bioactive sensing region, which produces an electrochemical signal. The signal is amplified by a device-integrated electrochemical signal amplifier called a potentiostat and is converted into a digital signal by an analog-to-digital converter (ADC), which securely transmits the data via encrypted Bluetooth to a paired device. This functionality supports real-time analysis by an AI-powered diagnostic platform, thus allowing detection of cardiovascular disease risk associated with dysbiosis in the gut microbiome.

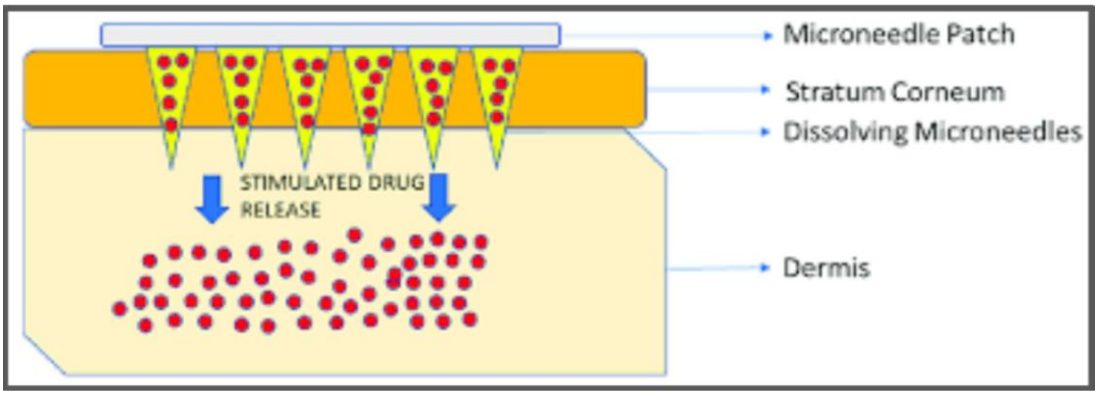

Figure 3: The figure depicts how an array of dissolving microneedles penetrates through the outermost layer of the skin (the stratum corneum) and deceased into the dermis. After insertion, the microneedles dissolve and release their contents (which can include sensing agents or therapeutic compounds) into the interstitial fluid part of the skin. This makes it possible for sampling or delivery that is minimally invasive, allowing for real-time monitoring of biochemical markers like TMAO and SCFAs that are linked to gut microbiome activity and cardiovascular risk. The figure also visually helps to show how this can be considered a less invasive option compared to traditional means by using the skin as a continuous and accessible interface for diagnostics

6. Comparative Analysis with Existing Diagnostic Tools

Compared to existing cardiovascular diagnostic tools, our AI-powered microneedle patch system provides a unique advancement by targeting microbiome-related biomarkers. Traditional diagnostics, such as blood pressure monitors, ECGs, and cholesterol tests, focus mainly on physiological metrics and often fail to detect early-stage disease or consider the role of the gut microbiome (Chen et al., 2016; Koh et al., 2016).

Consumer wearables like the Apple Watch or Fitbit can track heart rate and rhythm, but do not measure biochemical markers that may signal deeper inflammatory or microbial imbalances linked to cardiovascular conditions (Zhao et al., 2021). Even advanced lab-based diagnostics, like blood panels or stool microbiome testing, are expensive, require professional interpretation, and are not accessible in many low-resource settings (Zhang et al., 2020).

Unlike these tools, our microneedle patch provides real-time detection of microbial metabolites such as TMAO and SCFAs, which are strongly linked to cardiovascular risk (Chen et al., 2016; Koh et al., 2016). It uses biorecognition molecules on microneedles to detect specific microbial biomarkers and sends encrypted signals to a user-friendly AI platform that interprets the results. The AI system, trained on symptom data, also functions independently to predict disease risk based on user input (Zhao et al., 2021). Most importantly, this solution is designed to be low-cost and easy to use, making it especially impactful in underserved areas where advanced diagnostics are limited. By integrating the microbiome into cardiovascular screening, our platform expands the scope of early detection and prevention in a way that existing tools simply cannot.

Table 2: Comparison of Cardiovascular Diagnostic Tools

Feature	Blood Pressure Monitor	ECG	Blood Test (Lipid Panel)	Stool Microbiome Testing	Microneedle AI Patch
Measures Physiological Metrics	Yes	Yes	Yes	No	Yes
Detects Biochemical Biomarkers	No	No	Yes	Yes	Yes
Includes Microbiome Analysis	No	No	No	Yes	Yes
Provides Real time Data	Yes	Yes	No	No	Yes
Requires Lab or Clinic	No	Yes	Yes	Yes	No
AI Based Risk Prediction	No	No	No	No	Yes
User friendly Interface	Yes	No	No	No	Yes
Cost effective	Yes	No	No	No	Yes
Accessible in Low resource Settings	Yes	No	No	No	Yes

7. Case Study

Scenario 1: Rural Preventive Screening

A 52-year-old male living in a rural village with limited access to healthcare visits a community clinic complaining of occasional chest tightness and fatigue. The clinician applies the microneedle biosensor patch, which non-invasively detects elevated levels of trimethylamine N-oxide (TMAO), a gut-derived metabolite associated with cardiovascular risk. In real time, the AI diagnostic platform combines this biochemical signal with the patient's self-reported symptoms and calculates a moderate to high risk score. The platform recommends immediate referral to a cardiologist. This is an example of catching the risk early in an environment where delayed diagnoses are common.

This scenario is particularly pertinent given that rural residents face significantly higher cardiovascular mortality rates compared to their urban counterparts. For instance, in 2019, the age-adjusted death rate from heart disease among adults aged 45–64 years was 160.0 per 100,000 in rural counties, compared to 114.5 in urban counties (Centers for Disease Control and Prevention [CDC], 2021). Moreover, nearly half of U.S. counties lack a practicing cardiologist, with 86.2% of these being rural counties, exacerbating the challenges in accessing specialized cardiovascular care (American College of Cardiology [ACC], 2024).

Scenario 2: Urban Lifestyle Monitoring

A 35-year-old professional in an urban setting uses the biosensor patch as part of her wellness tracking routine. Over several weeks, the patch logs short-chain fatty acid (SCFA) fluctuations and minor elevations in TMAO post high-fat meals. Although she reports no symptoms, the AI system detects a subtle but consistent trend associated with early metabolic imbalance. It issues a low-risk notification with personalized dietary recommendations, helping her adjust her lifestyle before clinical symptoms emerge. This kind of proactive intervention aligns with the goals of preventive medicine, which emphasizes early detection and modification of risk factors to avoid disease onset.

Moreover, wearable health technologies have increasingly shown promise in enabling real-time monitoring and personalized feedback loops that encourage sustained behavior change. This feedback loop empowers long-term prevention through behavior change, supporting recent trends in digital health where biosensors and AI analytics guide users toward healthier patterns before disease manifests.

Scenario 3: Post-Discharge Monitoring

A 68-year-old patient recently discharged after a mild cardiac event uses the patch for remote follow-up. The AI platform continuously monitors both symptom input and biomarker recovery trends, identifying potential complications such as increased gut permeability linked to inflammatory responses. After being alerted by abnormal readings, the system notifies the patient's cardiologist, which allows them to have a quick teleconsultation and medication adjustment without requiring a hospital visit.

8. Discussion

The convergence of microbiome science, microneedle sensor technology, and AI has presented a transformational opportunity to approach the domain of cardiovascular diagnostics, especially in regions with poor infrastructure. This study discusses an inventive platform that attempts to bridge key gaps in early CVD detection, access, and personalized risk assessment.

Introducing a microneedle patch for the detection of microbial metabolites (TMAO, short-chain fatty acids) addresses a critical inability of traditional diagnostics outcomes, which produce a lack of biochemical insight into the gut-heart link. Emerging evidence now firmly establishes that dysbiosis of gut microbiota-related systemic inflammation occurs in endothelial dysfunction and lipid metabolism, being hallmarks of cardiovascular pathology (Alaband et al., 2018). Yet, such biomarkers are virtually absent from any current wearable technologies reliant on generalized physiological data such as heart rate and ECG. This biosensor patch, therefore, serves as an innovative step forward with minimal invasiveness for continuous, real-time monitoring of these select signals right out of interstitial fluid(Li et al., 2024).

In addition, our AI-assisted platform greatly improves the diagnostic performance of such tools as well as ease of usability. With the integration of the trained neural network that accepts input from the biosensor in real-time with symptoms reported by the user, the required dual-mode screening: biochemical and symptomatic, rendering the tool specific(Smith et al., 2024).

9. Ethical and Privacy Considerations

As with any AI system handling sensitive data, ethical and privacy concerns are essential to address. First, data privacy must be prioritized, especially as the model expands to incorporate electronic health records, biosensor outputs, or personal health histories. Ensuring strong data protection requires robust anonymization techniques, secure data transmission, and compliance with privacy regulations such as HIPAA and GDPR. These safeguards are critical for maintaining user trust and protecting individual rights in both clinical and non-clinical settings.

Another major consideration is the presence of bias in AI models. Machine learning systems are only as fair as the data they are trained on. If a model is trained on imbalanced or non-representative datasets, it risks producing skewed predictions that disproportionately affect underrepresented populations. This can lead to reduced diagnostic accuracy and reinforce existing health disparities. It is crucial to ensure that training data includes a wide range of demographic, geographic, and clinical profiles. Continuous auditing and monitoring of model outputs are also necessary to detect and address any emerging biases over time, especially as real-world usage introduces new data sources.
Lastly, it is important to know the unreliability of self-reported symptoms, which presents a practical limitation in AI-driven diagnostics. Individuals may unintentionally misreport, minimize, or exaggerate their symptoms due to factors such as misunderstanding medical terminology, forgetfulness, or personal interpretation of discomfort. These inconsistencies can lead to reduced accuracy in model predictions and may compromise the reliability of the system's risk assessments. To mitigate this, AI platforms will be designed to include features such as clarification prompts, detailed symptom definitions, and structured follow-up questions that help guide users in providing more accurate information. By enhancing user input through these methods, we can increase the consistency and clarity of the data collected. Moreover, integrating self-reported symptoms with objective data from biosensors can also improve the model's performance. The combination of subjective user inputs and quantifiable biochemical signals will allow for a more balanced and comprehensive diagnostic approach, which will ultimately lead to more accurate and personalized health evaluations.

10. Limitations and Future Directions

The availability and specificity of antibody-coated targets naturally limit the repertoire of detectable biomarkers, while the sensitivity of the microneedle patch and the amount of interstitial fluid it can sample place upper bounds on detection thresholds. Variations in skin permeability, the biochemical stability of microbial proteins, and the requirement for precise calibration under various physiological and environmental conditions further complicate consistent performance. Despite these practical limitations, our platform does represent a significant advancement. Furthermore, using user-reported symptoms and a synthetic dataset to train the neural network introduces biases resulting from oversimplified symptom-disease mappings, a lack of real-world variability, and inconsistent self-reporting, wherein intentional misreporting, recall bias, or misunderstanding may distort input data and impair predictive accuracy.

Beginning with small-scale feasibility studies to evaluate safety, tolerability, and preliminary efficacy in detecting microbial biomarkers in healthy volunteers, a rigorous validation pathway is needed to move from prototype to clinical tool. Phase I/II clinical trials in a variety of patient cohorts are then necessary to establish diagnostic accuracy, sensitivity, specificity, and clinical utility in comparison to gold standard assays. All of these trials must be carried out under ethical supervision and in accordance with regulatory guidelines. In order to improve the AI component going forward, it will be necessary to: adopt federated learning architectures to leverage decentralized healthcare data without compromising privacy; integrate annotated real world datasets drawn from diverse populations and longitudinal studies to refine model training; and embed continuous user feedback loops that enable on device or cloud based model retraining, which will improve personalization, reduce bias, and guarantee that the diagnostic platform adapts dynamically to changing clinical insights and patient needs.

11. Conclusion

This project demonstrates the potential of AI-driven diagnostic tools by successfully building a symptom-based

disease prediction prototype using a Multilayer Perceptron. While effective on synthetic data, clinical reliability remains limited until the model is trained and validated on real-world patient data. The next key steps include incorporating electronic health records, expanding inputs (such as symptom severity and duration), and exploring advanced neural architectures or ensemble models. Our findings offer a foundation for accessible and early-stage diagnostic support, particularly valuable in underserved healthcare settings, and mark a promising step toward intelligent digital triage systems that complement and extend medical care. Importantly, this research contributes a framework for early diagnostic support, especially valuable in resource-limited environments where medical expertise is scarce. By bridging structured symptom data and machine learning, we lay the groundwork for intelligent triage systems that can reduce diagnostic delays and ultimately improve health outcomes. Continuing investigation will help answer key questions around model real-world accuracy and clinical adoption, which pushes this work from prototype toward practical impact.

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