# PPG Earring: Wireless Smart Earring for Heart Health Monitoring


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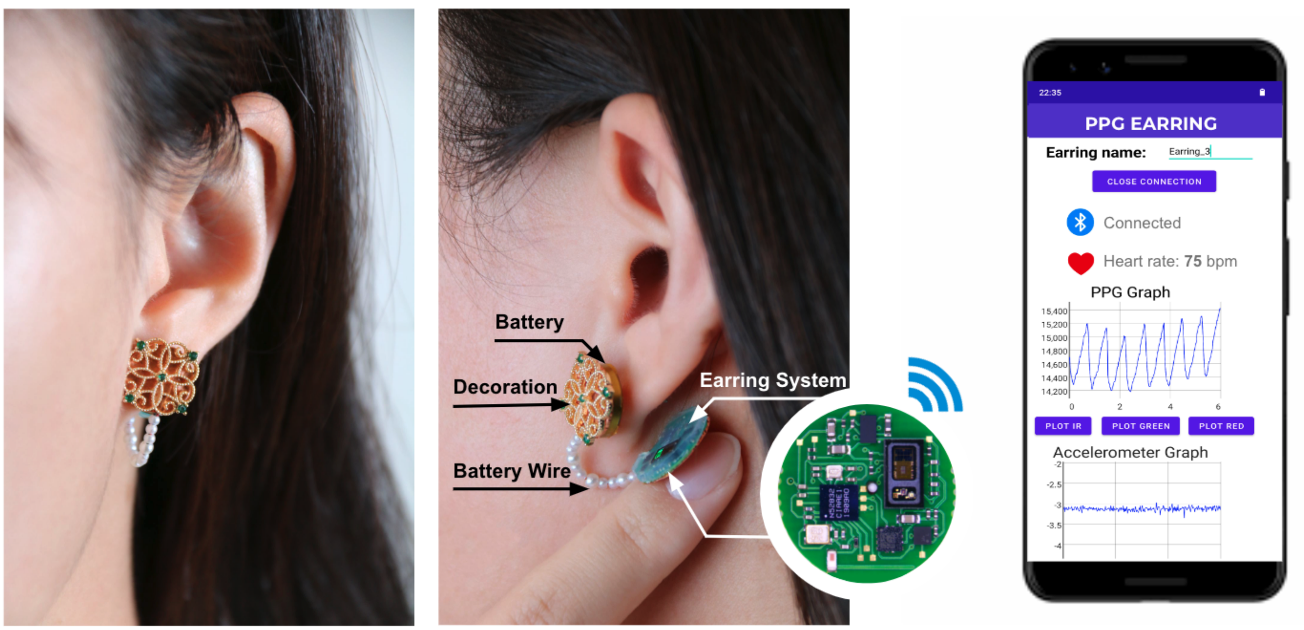


(a) PPG Earring front view (b) PPG Earring side view (c) PPG Earring App

**Figure 1: (a) (b) The front and side view of PPG Earring with fashion design. (c) The smartphone app that connects to PPG Earring through Bluetooth and displays real-time PPG signal.**


## Abstract

Heart rate is a key vital sign for cardiovascular health and fitness. However, the photoplethysmography (PPG) sensors that monitor heart rate in wearables struggle with accuracy during motion. Our day-long in-the-wild study shows Fitbit measures valid heart rates only 54.88% of the time. To address this, we developed PPG Earring, which measures 14 mm in diameter, weighs 2.0 g, and offers 21 hours of continuous sensing. Our eight-user exercise study shows that PPG Earring captures valid heart rate data for 91.74 ± 4.84 % of the time during exercise and 86.29 ± 2.96% of our day-long in-the-wild study. All participants found the PPG Earring as comfortable as their regular earrings, and most participants expressed a strong willingness to wear the PPG Earring all the time every day. Our results validate the signal quality and comfort level of the PPG Earring, highlighting its potential as a daily health monitoring device.




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## CCS Concepts

**• Human-centered computing → Ubiquitous and mobile computing systems and tools**; **• Applied computing → Consumer health**.

## Keywords

Wearable Computing; Health monitoring; PPG; Smart Jewelry; Smart Earring

**ACM Reference Format:**

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## 1 Introduction

Integrating heart rate monitoring into daily routines using wearable technologies can empower individuals to stay proactive about their health. Heart rate provides numerous insights into cardiovascular health. Abnormal heart rates, whether too fast (tachycardia) or too slow (bradycardia), can signal a variety of underlying health conditions. The ability to track heart rate during exercise could also help maintain controlled intensity and optimize fitness benefits or even provide warnings of dangerous overexertion for individuals with cardiovascular disease. While heart rate monitoring is now widely available through devices like smartwatches and smart rings, their underlying sensing principle makes it challenging to produce accurate, continuous measurements during exercise.

These devices use photoplethysmography (PPG) to measure the heart rate by shining a light into the skin and capturing the light reflected by the blood vessels. One of the biggest challenges of using PPG for continuous heart rate sensing on wearables is dealing with motion artifacts. Because PPG measures reflected light to detect blood volume changes caused by heartbeats, any small movement or pressure change between the skin and the PPG sensor can cause a change in the light path. This results in substantial noise in the sensed PPG signal making it extremely challenging to measure heart rate during activities ranging from intense exercise to walking. Current wearables like smartwatches and smart rings often address this issue by either discarding noisy data or applying advanced processing methods to estimate or interpolate the heart rate [5, 15, 58, 61]. Although various processing methods, such as using motion sensor data to compensate for PPG motion artifacts [16, 38], have been explored, their estimation accuracy remains very limited due to the inherently poor quality of PPG data during motion [2, 41, 57].

In this work, we propose an alternative wearable heart rate monitoring solution that addresses this problem: smart earrings. The earlobe, like the fingertips, is a well-known site for clinical PPG measurement due to its rich blood flow near the skin's surface. The thin skin of the earlobe allows PPG light to penetrate more easily, enhancing signal quality. Additionally, humans have evolved sophisticated sensory-motor mechanisms to stabilize the head, even during exercise and motion [35]. This, combined with the constant, stable contact between the PPG sensor and the earlobe enabled by the earring, results in substantially lower motion artifacts compared to loosely worn watches and rings.

However, developing smart earrings requires overcoming multiple challenges. Earrings are significantly smaller than watches, leaving much less space for the sensing electronics and a battery. In addition to fitting within the limited dimensions of the earlobe, weight is also a critical constraint for earring form-factor devices. A heavier earring not only causes discomfort but also increases movement, which degrades the PPG signal quality. This introduces strict constraints on the battery, typically the heaviest component in the system, which must be small and lightweight while supporting continuous system operations. This is particularly challenging for PPG sensing, which requires 10-50 mA of current to produce sufficiently bright light for reliable signal acquisition.

In this paper, we address these challenges and develop PPG Earring: the first compact smart earring capable of monitoring user heart rate through PPG on the earlobe. As shown in Figure 1, the PPG Earring prototype mimics the form factor of standard earrings, measuring 14 mm in diameter and weighing 2.0 g. Our sampling strategy, which only emits light in brief microsecond pulses to capture each PPG sample, enables 21 hours of *continuous* PPG and motion sensing at a sampling rate of 50 Hz. This can be further extended to roughly 17 days when performing opportunistic sensing—for example, monitoring PPG and motion for 30 seconds every 10 minutes. Beyond heart rate, the PPG sensor can also measure heart rate variability (HRV) for stress insights and blood oxygen saturation (SpO2). Additionally, the earring includes a temperature and an accelerometer sensor, making the PPG Earring a versatile health monitoring platform.

We systematically evaluate PPG sensing signal quality at the earlobe, compared to the wrist and finger with the same PPG light strength settings. Our experiment results demonstrate that the earlobe provides up to 6.3x (8.0 dB) higher signal quality than the wrist across various light settings and up to 2x (3.3 dB) better than the finger. Notably, earlobe-based PPG sensing proved particularly more effective than hand-based sensing for users with cold hands. In our exercise study, we compared PPG Earring's performance with a commercial Fitbit during walking, running, and weightlifting. The results revealed that the PPG Earring captured valid heart rate data for an average of 91.7% of the exercise time, significantly higher than the Fitbit's 67.2%.

In addition to controlled studies, we conducted a real-world study involving six participants wearing the PPG Earring and a Fitbit for a day (around 8-12 hours during the daytime) while continuing their natural activities. PPG Earring captured valid heart rate signals $86.29 \pm 2.96\%$ of the time, while Fitbit only captured $54.88 \pm 4.63\%$ time. All participants found PPG Earring to be as comfortable as their regular earrings. Five out of six participants expressed a strong willingness to wear the PPG Earring daily. Four participants showed a strong preference for the PPG Earring over the Fitbit, describing the earring as so comfortable that they "didn't even feel it," while the smartwatch was perceived as "bulky and uncomfortable." This in-the-wild study validated the comfort level of the PPG Earring and highlighted its potential as a reliable daily health monitoring device.

In summary, we present the following **contributions** in this paper:

- We designed the first smart earring for heart rate monitoring that is in a form factor similar to normal earrings. The PPG Earring has a 14 mm diameter, weighs just 2.0 grams—comparable to typical earrings—and provides a battery life of 21 hours with continuous PPG sensing and Bluetooth transmission.
- We compared the earring's PPG signal quality to wrist- and finger-based sensing, demonstrating that the earring achieved 2-6.3 times (3.3-8.0 dB) better signal quality with lower power consumption and was affected by motion artifacts for 10%-37% less time during activities.
- We compared PPG Earring with a commercial Fitbit smartwatch during exercise and a whole-day in-the-wild study. PPG earring was able to capture heart rate data for $91.74 \pm 4.84$ % of the time during exercise, which is 24.5% higher than Fitbit. PPG Earring captured valid PPG for $86.29 \pm 2.96$% of time during in-the-wild study, which is 32% higher than Fitbit and has a 2.2 times (3.4 dB) higher SNR.
- The PPG Earring was rated as highly comfortable by all six participants in the whole-day in-the-wild study. All participants found it as comfortable as their regular earrings, with five participants expressing a strong willingness to wear it all the time every day.

# 2 Related Work

## 2.1 Smart Jewelry and Fashion Accessories

Smart jewelry is an emerging class of wearable devices that seeks to combine fashion and function by integrating sensing into jewelry accessories. Previous research in smart jewelry has explored various functional items: smart necklaces, bracelets, glasses, rings, earrings, and nails. Smart necklaces have been being utilized for applications such as silent speech recognition [75], eating detection [76], medication adherence [31], and posture correction [17]. Research on bracelets has spanned areas like user interaction [23, 68], health monitoring [4, 22], and personal safety automation [49]. Rings have also been explored for their interacting and health monitoring capabilities [6, 40, 46, 62, 77]. However, smart earrings have been less explored, with limited research focusing on wellness tracking [47, 54] and audio sensing [30, 51], often featuring larger than desired form factors. Thermal Earring is a wireless smart earring similar to a common dangling earring, but it focuses on earlobe temperature monitoring instead of heart health [72]. The smart nail has been investigated as a gestural input surface [32] and for sensing fingernail deformation [28]. Additionally, nose rings have been developed for electrical trigeminal stimulation [11]. A significant challenge in the development of smart jewelry is maintaining the compact size typical of traditional jewelry—a goal that most of the current research has not yet achieved. Maintaining this compactness is essential for both the practical usability and aesthetic appeal of these smart jewelry devices.

In addition to smart jewelry, researchers have broadened the scope of wearable technology by incorporating other fashion elements into smart wearables [34]. This includes electronics tattoo [3, 7, 8] and painting [33, 37, 64]. Other innovations that combine smart wearables with fashion include smart clothes and buttons [20, 43, 67, 69], smart textiles [37, 66, 74], as well as novel concepts like smart hair [44] and smart makeup [39]. These developments highlight a trend towards integrating technology with stylish accessories, enhancing both functionality and aesthetic appeal.

## 2.2 PPG Sensing

PPG sensing provides valuable insights into heart rate and cardiovascular health, making it a popular choice for wearable health monitoring. Many commercially available devices, such as the Apple Watch and Google's Fitbit, have integrated PPG technology to track heart rate and detect anomalies like arrhythmias. More recently, wearables like the Oura Ring have also incorporated PPG sensors for heart rate monitoring from the finger. In addition to these mainstream wearables, researchers have explored PPG sensing in other form factors, such as smart glasses [19, 27]. Glabella [27] investigated PPG sensing on smart glasses and used it to estimate blood pressure. PPG sensing around the ear has also gained attention, with mainly earbuds being studied for their potential to detect heart rate signals through in-ear PPG measurements [21, 48]. There have also been prior explorations of smart earrings for PPG sensing [54, 60]. These designs often result in a significantly larger form factor, presenting challenges in terms of user comfort and signal quality due to motions caused by device weight. Besides sensing PPG using wearables, researchers have also explored PPG sensing using phone camera light [70], and there are also remote PPG sensing by capturing subtle facial color changes using cameras [52, 53, 71].

PPG sensing being affected by motion artifacts is a well-known problem and there have been a lot of explorations using various methods to address the motion artifact problems, such as using an accelerometer signal on the same wearable device to cancel out the motion signal in PPG [10, 42], or use advanced deep learning methods to recover PPG signal from heavily distorted signal [9, 14]. Besides using PPG for heart health monitoring, researchers have extended the PPG sensing capability to other activity sensing or interaction applications [13, 73].

# 3 Smart Earring Need Finding

To understand people's current experience and needs for wearable devices, as well as specific user requirements for smart earrings, we conducted semi-structured interviews for smart earring user need finding.

## 3.1 User Interview

*3.1.1 Participants and Procedure.* We recruited 13 US-based individuals who expressed interest in both health tracking and earrings. The interview study was conducted with Institutional Review Board (IRB) approval, and the participants were compensated for their time. The participants included 10 females, 2 males, and 1 non-binary individual, representing a range of ages (18 to 64 years old) and geographic locations. These participants worked across different industries, including retail, healthcare, technology, government, apparel design, information desk, event, and education, with education levels ranging from a high school diploma to a master's degree or higher. Participants reported using a variety of health-tracking devices, with many having experience across multiple products. Specifically, 8 participants had used Fitbit, 7 had Apple Watch, 2 had

Garmin smartwatch, 2 had Samsung Watch, and 2 had Oura Ring. Some also reported using less common devices, such as Letscom and Jawbone trackers. Interviews were conducted remotely via Zoom, which focused on three primary topics:

(1) People's earring-wearing habits and preferences.
(2) Usage patterns, likes, and dislikes related to popular health monitoring wearables.
(3) User requirements and expectations for smart earrings.

*3.1.2 Findings.* From participants' interview responses, we extracted key insights regarding people's earring-wearing preferences, experience with health-tracking devices, and expectations for smart earrings.

**Earring Wearing Preferences:**

The majority of our participants (12 out of 13) preferred lightweight and small earrings for daily use: *"[For weight, I prefer] the lighter the better, and the size. Maybe like if it's a stud, I would think the size of a fingernail."* (P6). Additionally, six participants identified comfort level as a crucial factor significantly affecting their willingness to wear earrings.

**Experience with existing health-tracking devices:**

Many participants (9 out of 13) found health-tracking devices helpful in improving health awareness. *"I think it just helps me to keep my health at the front of my mind. It offers an opportunity to explore what else I can improve in my health."* (P13). Six participants also highlighted the convenience of integrating health-tracking devices with the smartphone ecosystem. *"Sometimes you're in a meeting and maybe you're missing a call, but you can at least check your message, and you see that it's something very urgent, you can just step out."* (P6). These findings suggest that health-tracking devices not only improve health awareness but also enable convenient smartphone interactions.

However, participants also identified factors that have undermined their health-tracking experience, including:

- **Discomfort:** Discomfort was a common issue leading to the abandonment of certain products among five participants: *"The Fitbit band has electromagnetic. My skin got a rash, and I stopped using it."* (P2); *"I tried an Apple Watch for a bit. I got kind of annoyed, so I stopped and I gave it to my daughter. I use the band that it came with. Maybe there's a more comfortable band out there, but I just, I don't like things on my wrist."* (P1).
- **Inaccuracy:** Four participants expressed frustration with inaccurate or contradictory health data: *"I honestly don't think it's super accurate. Sometimes I'm walking, or like I'm not doing anything. And they'll say that I'm walking indoors or I'm exercising. And that's not. Sometimes, it's giving wrong feedback. So I don't really trust it that much."* (P4).
- **Appearance:** Six participants stressed the importance of an attractive design: *"With the Oura ring, I feel like it kind of looks like an accessory. It's not necessarily a tracking device. It's supposed to be maybe a little bit more stylish."* (P5). Two of these participants further emphasized that the design should be flexible enough to match well with their outfits: *"But like a nice looking smartwatch, it just blends in. I don't wanna have to have backup watches like regular watches and stuff like that. So I don't even have to wear those. So I want something that could replace all of those, so appearance is really important."* (P12).

**User Adoption of Smart Earrings:**

11 out of 13 participants were willing to use smart earrings for everyday purposes. Furthermore, five participants mentioned that smart earrings would meet their needs better than other devices, including smart watches (2 participants), smart rings (2 participants), and smartphones (1 participant). These findings suggest that smart earrings may offer a more convenient and comfortable health-tracking experience, especially for people wearing earrings as a daily routine.

Similar to participants' preferences in other health-tracking devices, appearance and design were particularly important. Seven participants listed design as one of their top three desired features, highlighting the need for the smart earrings' aesthetic appeal in addition to reliable and accurate health-tracking functionality.

## 3.2 Smart Earring Design Requirements

Smart earrings demonstrate strong potential as a comfortable and convenient health-tracking wearable. Our discovery user research provides valuable insights into key design requirements, which will help ensure the successful adoption and long-term use of the smart earrings.

- **Enhanced Comfort:** Comfort is a crucial consideration for both daily earring use and health-tracking wearables. The vast majority of participants emphasized the importance of lightweight earrings for daily wear. Comfort was also identified as an important factor influencing people's willingness to frequently wear health-tracking devices. Ensuring a comfortable wearing experience for the smart earrings is pivotal for higher user adoption and retention.
- **Accurate Tracking:** Participants experience confusion and frustration with inaccurate or contradictory data. Therefore, more testing is necessary to ensure the accuracy and reliability of smart earrings' data to help alleviate these concerns and enhance the product's credibility.
- **Attractive Design:** Given the accessory nature of earrings, participants have high expectations for the aesthetic appeal of the design. Additionally, many participants expressed a preference for customizable designs that can match various outfits and occasions. An attractive design will enhance users' motivation to wear smart earrings more frequently.
- **Integration with Phone:** Integration with smartphones was a highly valued feature among participants. This feature allows users to check and preview messages, providing a greater sense of control when they're occupied with other activities. Some participants suggested that even partial integration, such as receiving notifications or vibrations for messages or fitness progress, will enhance the smart earrings' user experience.

Other considerations mentioned include intuitive health data visualization, accreditation of safety use, and offering free trials for subscriptions. While these features were not prioritized in the current design iteration due to limited time and resources, they provide valuable insights for future iterations.

## 4 PPG Earring System Design

Creating compact, low-power wearables like smart jewelry brings unique advantages and significant challenges due to their need for comfort and wearability. Key considerations include managing size, weight, and power consumption, all of which are often tightly interrelated and critical for ensuring comfort. We summarize the goal of our system design here: 1)

- **Compact Size:** The earring must be small enough to fit comfortably on the earlobe.
- **Lightweight:** The earring should be light to avoid any discomfort during long-time wear.
- **Reasonable Battery Life:** Despite form factor constraints, the earring should offer a reasonably long battery life without frequent recharging.
- **Universal Design:** Instead of customizing the system with various fashion designs, we developed the PPG Earring system into a universal earring backing design that can be worn together with any fashion design in the front.

PPG Earring achieves these design considerations and presents a practical wearable platform for longitudinal health sensing, offering typical health monitor capabilities such as heart rate, activity level, and body temperature. Next, we will detail the key components of the PPG Earring system, including the PPG sensor, motion sensor, microcontroller, and battery.

### 4.1 PPG Sensing

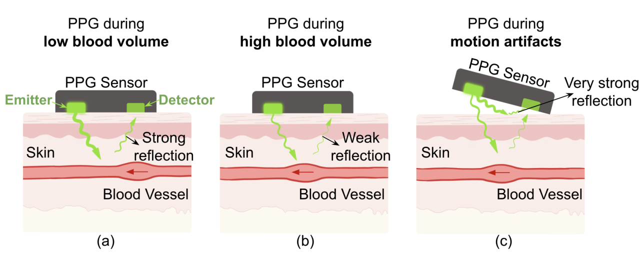


**Figure 2: Demonstration of how PPG light reflects under different conditions: (a) when the emitted PPG light is not on the blood pulse (low blood volume, absorbing less light), (b) when the emitted PPG light is on the blood pulse (high blood volume, absorbing more light), and (c) when motion artifacts cause a portion of the PPG light to be directly reflected by the skin.**

PPG is a noninvasive and low-cost optical measurement method that is often used for heart rate and SPO2 monitoring. As shown in Figure 2 (a)(b), a PPG sensor contains a light source and a photodetector and is placed in contact with the skin. When the light source emits light, the amount of light received by the photodetector varies as the blood volume in the vessels changes. This variation in blood volume affects the amount of light absorbed by the tissue, which in turn changes the amount of light received by the photodetector. The PPG sensor captures this signal, which can then be analyzed to derive useful information about cardiovascular health. PPG sensors typically use green (500–570 nm), red (600-750 nm), or infrared (IR, 850-950 nm) light to measure the blood volume change. Shorter wavelengths, like green light, have shallow skin penetration but are less affected by motion artifacts due to the shorter light path [38]. This makes the green light ideal for areas with good blood perfusion near the skin. In contrast, red and IR light penetrates deeper into tissue and can provide better signal quality when stable. They are also more suitable for oxygen saturation measurement.

Several factors can affect the PPG signal quality. One of the main factors is motion artifacts and the contact pressure between the sensor and the skin. As shown in Figure 2 (c), when a small movement happens, the PPG sensor can be slightly shifted from the skin which largely changes the optical path, resulting a significant different signal reflected to the photodetector. The appropriate amount of pressure between the PPG sensor and the skin is crucial, as too much pressure can reduce blood flow, while too little pressure may lead to poor contact and a lot of movements.

We implemented the PPG sensing on the earring using MAX30101 from Analog Devices, as shown in Figure 3. The MAX30101 senses the PPG signal through reflective PPG and is an integrated pulse oximetry and heart-rate monitor module that includes internal LEDs, photodetectors, optical elements, and low-noise electronics with ambient light rejection. In addition, the sensor has an integrated cover glass for optimal and robust performance. MAX30101 comes in a tiny package of 5.6 mm x 3.3 mm x 1.55 mm and features a low power consumption of less than 1 mW (varies with light intensity setting). The MAX30101 integrates red, green, and IR LEDs with programmable light strength from 0 to 50 mA. The LED pulse width can be programmed from 69 µs to 411 µs to allow balancing PPG accuracy and power consumption based on use cases. In our setup, we experimented with all lights and different light power settings in later Section.6.1. The MAX30101 PPG sensor is connected to the system microcontroller through an I2C line and is programmed to a sampling rate of 50 Hz.

Beyond PPG, the MAX30101 sensor can also measure blood oxygen saturation (SpO2), similar to many pulse oximeters. Low SpO2 levels may signal respiratory or circulatory issues, with readings below 92% often requiring immediate treatment to prevent organ damage [18]. The SpO2 monitoring from the earring can provide timely assessments to help verify if the respiratory and circulatory systems are working properly. However, a comprehensive evaluation of SpO2 accuracy would require extensive experiments and is, therefore, beyond the scope of this paper.

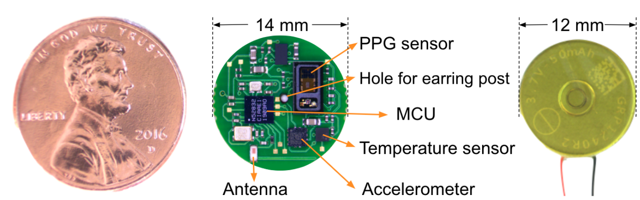


**Figure 3: The PPG Earring system PCB with a US penny coin as reference, and the battery for PPG Earring.**

### 4.2 Motion and Temperature Sensing

Although this paper primarily focuses on heart rate monitoring, we envision the PPG Earring to be a versatile health monitoring platform, just like a smartwatch fitness tracker. We have integrated motion and temperature sensing into the earring to capture user activities and monitor body temperature. We implement the motion sensing part using the LIS2DW12 3-axis low-power accelerometer from STMicroelectronics.The LIS2DW12 sensor features a programmable acceleration sensing range, sensitivity, and sampling rate. LIS2DW12 is available in an ultra-compact 12-LGA package that measures 2.0 x 2.0 x 0.7 mm, with less than 2 uW power consumption during active sensing in low-power mode. In addition, the LIS2DW12 sensor has a built-in internal engine to process motion and acceleration detection, including fall detection, stationary/motion detection, tap gesture recognition, etc., which enables potential acceleration-triggered system wake-up to further optimize system power efficiency. The LIS2DW12 accelerometer is connected to the microcontroller with I2C lines. The accelerometer is set to a sampling rate of 50 Hz in low power mode, with a sensing range of ±2 g and sensitivity of 0.244 mg/digit. The temperature sensor is implemented using HDC2010 from Texas Instruments. This temperature sensor was chosen because of its small size ($1.49mm \times 1.49mm$), low power consumption (0.9 uW), and high accuracy ($\pm 0.2C$). The HDC2010 is connected to the microcontroller through an I2C line, with a sampling rate of once every second.

## 4.3 Wireless Communication and MCU

The sensed data from the wearable device should be processed and presented to the user via a smartphone or computer. Wireless communication, which involves high-frequency RF signals in the GHz range, typically consumes around 5 mW of power during transmission and is often the most power-intensive component of the wearable system. As a result, selecting a wireless communication method that is both energy-efficient and suitable for compact integration is crucial for optimizing the performance of the earring.

Bluetooth Low Energy (BLE) is the preferred choice for many wearable devices due to its low power consumption, suitable wireless range, and compatibility with smartphones and laptops. Given that most people have smartphones with them most of the time, BLE offers convenient data exchange between the smart earring and the smartphone. BLE connection mode is ideal for streaming data and provides high data throughput, which supports up to 251 bytes of data in each packet.

Considering these factors, we chose the nRF52832 microcontroller chip with built-in BLE capability for smart earring computing and wireless communication. This ultra-compact chip is packaged in a wafer-level chip-scale package, measuring 3.0 x 3.2 x 0.5 mm and weighing 6.8 mg. It incorporates an ARM Cortex M4 processor for computing tasks and has built-in Bluetooth low-energy transceivers with configurable transmitting power, making it an ideal choice for the earring wearable system.

Although the nRF52832 microcontroller is designed to be power-efficient, it still consumes around 3 mA in active mode and about 5 mA in Bluetooth transmitting mode, which is still very power-consuming for wearables with minimal battery capacity. In contrast, the nRF52832 chip consumes only 1 μA in deep sleep mode, significantly saving power. So, we configured the nRf52832 microcontroller to wake up only when needed to interface with the sensors or transmit BLE packets. Both the PPG and accelerometer sensors can store up to 32 samples of data in their FIFO, reducing the frequency at which the microcontroller needs to wake up to read sensor data.

When using a single light in the PPG sensor, each PPG sample consists of 3 bytes, each accelerometer sample (per axis) is 2 bytes, and each temperature reading is 2 bytes. To pack the measured data into a BLE packet (maximum size: 251 bytes), the earring system aggregates 25 samples of PPG and accelerometer data, along with 1 sample of temperature data, resulting in a total packet length of 25 samples x 3 bytes + 25 samples x 2 bytes x 3 axes + 1 samples x 2 bytes = 227 bytes. With both the PPG sensor and accelerometer configured to a 50Hz sampling rate, the microcontroller only needs to wake up every 25 samples x (1000ms/50Hz)=500ms to read the sensor data and send it via BLE. This approach minimizes the microcontroller's active time, significantly reducing its average current consumption. Further optimizations can be achieved by reducing the number of accelerometer samples sent or enabling accelerometer data streaming only during specific activity triggers.

## 4.4 Battery and Power Consumption

For wearable devices, and specifically smart earrings, the power source is a critical component that must have high power capacity while being compact and lightweight. As discussed before, wireless communication and powering the PPG sensor light consume the most power. On average, the total power requirement of the earring system is 2.2 mW when sensing and wirelessly transmitting PPG and accelerometer data at a 50Hz high sampling rate.

The energy limits of currently available battery technologies make batteries the largest and heaviest components in such small centimeter-scale devices. To achieve our target form factor, we chose the high energy density GRP1240 battery from Grepow. The GRP1240 rechargeable Lithium-ion battery offers a high capacity of 50 mAh with a diameter of only 12 mm and height of 4 mm. With the 50 mAh battery, the PPG Earring can achieve a battery life of 21 hours of continuous PPG sensing (single light) and accelerometer sensing both at 50 Hz. In addition, the battery life can be further extended to reduce the sensor sampling rate, we set both sensors to high sampling rate just to collect comprehensive data. In real-world scenarios, the PPG sensor can be set to opportunistic mode instead of continuous mode, such as only sensing for 30 seconds every ten minutes unless some specific activity happens. In theory, this can extend the battery life about 20 times longer, which makes a battery life of 17 days. The accelerometer can also be set to triggering mode, which only triggers when some interesting activities happen instead of continuously streaming accelerometer data.

## 4.5 The Final Earring System

As shown in Figure 3, the PPG Earring system is designed on a 14 mm diameter printed circuit board (PCB), making it smaller than a US penny. Since the average human earlobe measures around $19.6\text{mm} \times 18.8\text{mm}$ [12], PPG Earring can comfortably fit into most people's earlobe. None of our participants experienced any fit issues during the study. To ensure user comfort, as the device directly contacts the skin, a thin layer of skin-friendly silicone is applied to the surface of the PCB. This silicone layer is molded and cured at room temperature, providing a soft and comfortable interface for the user. Additionally, the silicone compensates for the height difference between the PPG sensor and other components on the PCB, creating a flat surface. The flat contact surface is essential

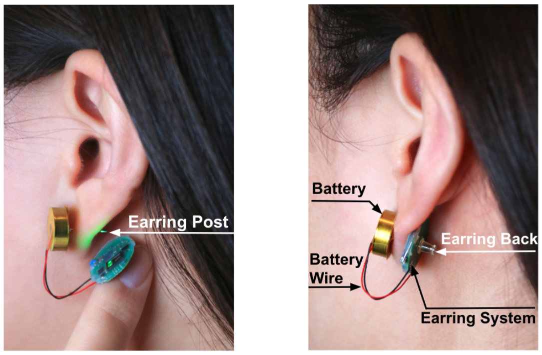


**Figure 4: Demonstration of how to wear the PPG Earring (without the decorative components).**

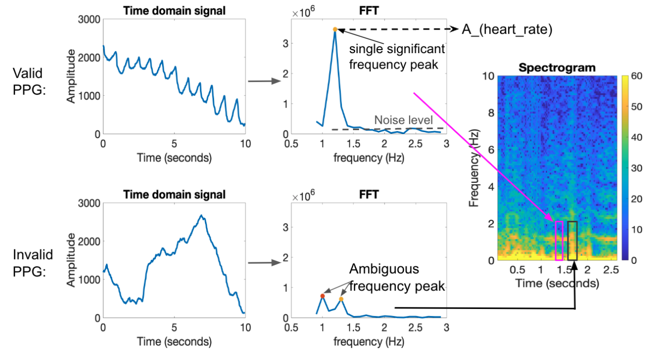


**Figure 5: An example of a valid PPG signal window and its FFT results, an invalid PPG signal window and its FFT results, and their corresponding representations in the spectrogram.**

not only for comfort but also to ensure consistent contact between the PPG sensor and the skin, which is critical for maintaining high signal quality. The entire earring system weighs just 2.0 grams, which is less than the average weight of normal earrings (around 3 grams)[29]. The individual component weights of the PPG earring are detailed in the table below.

The PPG Earring is worn similarly to a standard stud or hoop earring. As illustrated in Figure 4, the battery is positioned at the front of the earlobe like a traditional stud. A commercial earring post is attached to the battery, passing through the earlobe and the earring PCB. To maintain constant contact between the PPG sensor and the earlobe, a friction earring back is added behind the PCB to ensure optimal performance. Since the earlobe has good blood perfusion, placing the PPG sensor anywhere on the earlobe typically yields a reasonable PPG signal. To maintain a consistent setup in our studies, we instructed the participants to wear the earring with the PPG sensor positioned between the earring post and the head by rotating the earring system.

| Component | Weight |
|---|---|
| Earring PCB and electronics | 0.3 g |
| Silicone layer | 0.3 g |
| Battery | 1.4 g |
| Total | 2.0 g |

## 5 Signal Processing

We describe the signal processing pipeline for PPG signals, along with the definitions of the metrics reported in later sections. During the study, PPG Earring data is streamed to a smartphone app and stored in a local file with timestamps, while Fitbit data is recorded on the device and later transferred to a laptop for processing. All PPG signals from the PPG Earring and Fitbit are processed offline through the same pipeline using Matlab and Python. First, the PPG signals are segmented using a 10-second sliding window with a 5-second overlap. For each 10-second window, we compute the frequency distribution using a fast Fourier transform (FFT). Figure 5 shows examples of valid and invalid 10-second window signals with their corresponding FFT results. The FFT results are used to determine whether this 10-second window is a valid PPG signal or not and compute the Signal-to-Noise Ratio (SNR).

### 5.1 Valid PPG definition

The top of Figure 5 shows an example of a valid PPG signal and its corresponding FFT results. The valid PPG signal demonstrates a clear periodic pattern in the time domain, with a single dominant frequency peak in the possible heart rate range (50-180 bpm during daytime [56], corresponding to 0.8-3.0 Hz). The bottom of Figure 5 shows an example of an invalid PPG signal, which does not show a periodic pattern in the time domain and thus does not have a single significant frequency peak in the FFT results.

Based on the observation, We define and classify whether a 10-second window is valid PPG or not using the following criteria: 1) The FFT must have a single dominant peak, with an amplitude at least twice that of the second-highest peak. 2) The peak must be significant, at least twice the mean and median power of frequencies within the 0.8 Hz to 3.0 Hz range.

The right of Figure 5 shows a 2.5-minute spectrogram computed using STFT (where the FFT results are stacked vertically). The continuous line in the spectrogram reflects the heart rate over time, as the heart rate always changes gradually. Thus, a third criterion is applied based on this observation: during non-exercise periods, the current window's heart rate should be within 10 bpm (0.17 Hz) of the previous window's heart rate and within 20 bpm (0.33 Hz) during exercise.

The valid percentage of the PPG signal is the ratio of the number of 10-second windows that can be used to compute a valid heart rate to the total number of 10-second windows in the whole signal.

### 5.2 SNR definition

Signal-to-Noise Ratio (SNR) is a common metric to measure the level of the target signal compared to the level of background noise. In this paper, the SNR of the PPG signal is defined as the ratio of the power of the heart rate frequency bin to the average power of the frequencies within the possible heart rate range. Since our study only focuses on daytime conditions, we consider the typical human heart rate range of 50 to 180 bpm [56], corresponding to a frequency range of 0.8 Hz to 3.0 Hz. The SNR of the PPG signal is given by: $SNR = \frac{P_{heart-rate}}{P_{other-frequency}} = \frac{P_{heart-rate}}{(P_{0.8-3.0Hz} - P_{heart-rate})}$, where $P_{heart-rate} = A^2_{heart-rate}$ represents the power of the detected heart rate frequency and $A_{heart-rate}$ is its FFT amplitude.

$P_{other-frequency}$ refers to the average power of the noise floor, which is all frequencies within the 0.8 Hz to 3.0 Hz range excluding the heart rate frequency. The computed SNR result is then converted to decibels using $SNR_{dB} = 10 \times log_{10}(SNR)$.

## 6 Lab controlled studies

In this section, we present the results of the user studies, which validate the effectiveness and reliability of the PPG Earring. In the first study, We compared the performance of the sensing PPG from the earlobe with two common PPG measurement sites: the finger and wrist. The results show that sensing PPG on the earlobe provides much better signal quality than on the wrist and slightly better signal quality than on the finger. In addition, sensing PPG on the earlobe is not likely to be affected by motions, making earrings a much more reliable monitoring method than smartwatches and smart rings.

In the second study, we evaluated the PPG Earring's performance against a commercial Fitbit smartwatch during exercise. Our findings demonstrate that PPG Earring provides significantly more reliable heart rate monitoring during exercise compared to the Fitbit smartwatch.

All studies were conducted with approval from the Institutional Review Board (IRB), and users were compensated based on the specific studies in which they participated.

### 6.1 Earring vs. Ring. vs. Watch Study

The earlobe and finger are clinically optimal locations for measuring PPG due to their good blood perfusion, and the wrist has been a popular location on wearables, too, because it is convenient. In this study, we aim to compare these three measurement sites to determine if the earlobe offers a more efficient and reliable location for PPG heart rate monitoring than the finger and wrist.

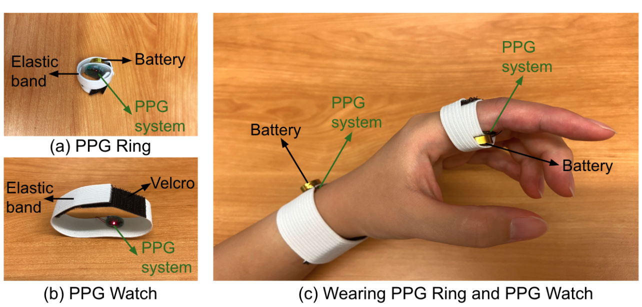


**Figure 6: (a) The PPG Ring is made from the same system as PPG Earring. (b) The PPG Watch is made from the same system as PPG Earring. (c) The demonstration of how users wear the PPG Ring and PPG Watch during the study. Both the PPG Ring and PPG Watch are attached to the user using an elastic band with velcro to adjust tightness.**

We recruited eight participants to collect PPG data in a lab-controlled environment. The participants included six females and two nonbinary individuals, with an average age of 31.1 ± 12.4 years. Their skin tones ranged from Type I to Type IV on the Fitzpatrick scale. Participants were asked to wear three devices — the PPG Earring, PPG Ring, and PPG Watch — all of which were made by the same PPG system so we can control light intensity. Figure 6 shows how the participants wear the PPG Ring and PPG Watch using an elastic band with velcro, which allows for adjustable, comfortable tightness. The participants wear the PPG Earring as shown in Figure4.

The PPG Earring, Ring, and Watch were configured to the same light intensity settings and programmed to collect PPG data using green, infrared (IR), and red lights simultaneously throughout the experiment. Additionally, we examined how different PPG light intensities affected signal quality. The minimum light intensity for all wavelengths was set to 3 mA, while the maximum intensity was either the highest level that did not saturate the sensor on participants' skin or the sensor's maximum capacity: 50 mA for green light, 24 mA for IR, and 30 mA for red. The medium intensity was defined as the average of the lowest and highest light intensities.

The study has two parts. 1) In the first part, the participants were asked to stay still while wearing the PPG earring, ring, watch, and a commercial pulse oximeter (BioRadio) as ground truth for two minutes. This part aimed to compare the PPG signal quality from different body locations under ideal, motionless conditions. 2) In the second part, the participants wore the PPG earring, ring, and watch while performing two common daily activities: using a phone and working on a laptop, with each activity lasting two minutes. The second part of the study was designed to assess the PPG signal quality during typical motions encountered in daily life. Both of the two parts of the study were repeated three times with three different light intensity settings.

#### 6.1.1 *PPG quality from earring vs. ring vs. watch during still.*

We compute the SNR results of the PPG signal collected from eight participants while they stayed still and did not move at all.

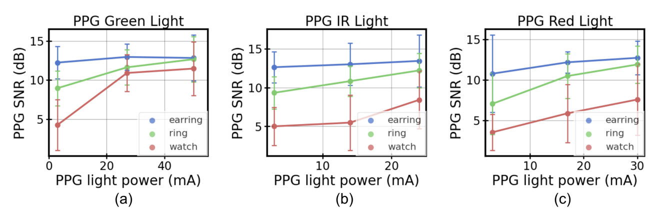


**Figure 7: The SNR of PPG signal from earring vs. ring vs. watch, (a) using green light, (b) using IR light, and (c) using red light.**

Figure 7 shows the PPG SNR results of the earring, ring, and watch with green, IR, and red light separately. The results show that the PPG signal obtained from the earring has a much higher SNR than the wrist for all lights and achieves a similar or higher SNR than the finger. It is expected since both the earlobe and finger have rich capillaries close to the skin surface, while wrist blood vessels are deeper and more sparse. In addition, we noticed that there were three participants who had significantly low-quality PPG signals from the ring. Two of the participants reported cold hands, and another participant had callused skin on the fingers, which likely contributed to the low SNR from the finger. These three participants' data contributed to the ring's overall lower average SNR compared to the earring.

In addition to signal quality differences across measurement sites, Figure 7 shows that as PPG light intensity decreases, signal quality diminishes across all locations. However, the earlobe consistently maintains acceptable signal quality even at lower light intensities, whereas the signal from the finger and wrist drops significantly. This is likely due to the thin skin of the earlobe, which allows light to penetrate more easily into the underlying capillaries. These findings highlight the PPG Earring's potential for high-quality, low-power heart rate monitoring, leveraging the natural advantages of the earlobe's thin skin.

Among the three PPG light types, IR and green light deliver similarly high signal quality across all intensities for both the earring and ring, with IR slightly outperforming green for the earring. This is expected since IR penetrates the skin better and is well absorbed by oxyhemoglobin. Green light also performs well, only 0.6 dB lower than IR at the highest intensity for the earring. While green light doesn't penetrate tissue as deeply, its higher power compensates, making it the best choice for the wrist, likely due to the wrist's muscle and tendon composition—explaining why commercial smartwatches use green light for heart rate monitoring. Red light consistently shows the lowest SNR across all locations, especially at lower intensities. In pulse oximeters, red light is used with IR to estimate blood oxygen saturation (SpO2), and is less effective alone for heart rate monitoring.

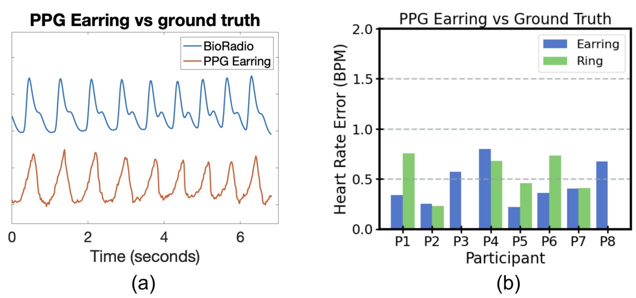


**Figure 8: (a) Example of the synchronized PPG Earring signal and the BioRadio signal. (b) The average absolute heart rate error of PPG Earring and Ring compared to the BioRadio ground truth signal.**

### 6.1.2 *PPG Earring vs. BioRadio as Ground Truth.*

We evaluated the PPG Earring's heart rate measurements against the commercial BioRadio pulse oximeter, which served as the ground truth because of its high signal quality and access to raw PPG data. BioRadio is widely used as ground truth in research [24, 26] for its reliability in physiological monitoring. Figure 8 (a) presents an example time-series plot comparing the PPG Earring's signal to the BioRadio's PPG signal from the same participant. The signals were synchronized offline using cross-correlation. The heartbeats align well between the two devices, although the PPG waveforms differ slightly. The shape difference arises because 1) the BioRadio employs transmissive PPG while PPG Earring and other wearable devices use reflective PPG [55, 59], and 2) the measurement sites are different (fingertip vs. earlobe).

Figure 8 (b) shows the average absolute heart rate differences computed from the PPG Earring device and the ground truth device, as well as the PPG Ring and the ground truth device. Heart rates were computed using a standard peak detection algorithm with a 10-second sliding window and a 5-second overlap. To isolate the system's heart rate monitoring accuracy from signal quality issues on the wrist or fingers, noisy data from the PPG Watch and PPG Ring (P2 and P8) were excluded. On average, the PPG Earring demonstrated a mean absolute difference of $0.45 \pm 0.21$ BPM compared to the ground truth device, while the PPG Ring showed a mean absolute difference of $0.55 \pm 0.22$ BPM (excluding P2 and P8). These results demonstrate the high heart rate monitoring accuracy of the PPG Earring.

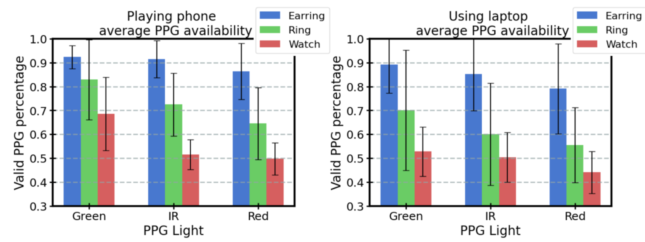


**Figure 9: (a) The average valid PPG percentage from the earring, ring, and watch while playing on the phone. (b) The average valid PPG percentage from the earring, ring, and watch while using the laptop.**

### 6.1.3 *PPG from earring vs. ring vs. watch during activities.*

In addition to evaluating the PPG signal when the user is perfectly still, we also explore the PPG performance on the earlobe, finger, and wrist when the user is using a smartphone or laptop. Figure 9 (a) and (b) show the valid percentage of PPG while playing on the phone and using laptops, respectively. During playing the phone, earring achieves $92.40 \pm 4.82\%$ with the best light results, while ring and watch only achieves $82.89 \pm 16.769\%$ and $68.61 \pm 15.35\%$ respectively. During using the laptop, the earring achieves $89.25 \pm 12.04\%$, while the ring and watch only achieve $70.12 \pm 25.19\%$ and $52.84 \pm 10.31$, respectively. The results showed that both ring and watch locations are more significantly affected by subtle motions during these daily activities. Though the earring's valid PPG percentage does not change much between playing on the phone and using the laptop, the ring and watch's valid PPG percentage significantly decreased when using the laptop, likely because of larger and more frequent hand motions when using a laptop, such as scrolling or typing. Besides different PPG sensing locations, different PPG lights also showed different performance during the same activity. Overall, green light always has the highest availability for the earring, ring, and watch, which means green light is less susceptible to motion artifacts. IR light has similar availability for the earring, but significantly lower availability for the ring and watch. And red light has the lowest availability across all devices. The results are expected as the green light is less susceptible to motion because of its shorter wavelength. IR light can penetrate more, so it is more likely to capture the internal muscle movement on the finger and wrist.

In summary, both green light and IR light can work well for the earring, while only green light might work well for the finger and wrist. The results of the study help guide future PPG sensing setups in different locations.

## 6.2 Exercise Study

Monitoring heart rate during daily activities and exercise is a key feature of modern wearables like smartwatches. However, capturing high-quality PPG signals during exercise is challenging due to strong motion artifacts caused by body movements.

To explore PPG Earring's heart rate monitoring capability during exercise, we recruited eight participants and conducted a semi-controlled exercise study. The participants consist of six females, one male, and one nonbinary gender, with an average age of 27.3 ± 5.4 and skin color range from type I to type V on the Fitzpatrick scale. The participants were asked to wear the PPG Earring at their comfortable tightness, and a commercial Fitbit smartwatch on their wrist at a tightness level that it will not move on the skin. The users were asked to complete three common exercise tasks at their comfortable level of intensity. The study included: 1) walking for five minutes, 2) running for five minutes, 3) performing nine sets of weight lifting using dumbbells. The weight lifting exercise included three sets of bicep curls, three sets of shoulder presses, and three sets of dumbbell rows. Each set includes ten repetitions. The total duration of the weightlifting exercise is around ten minutes, including rest periods. The total duration of the whole exercise study ranges from 20 minutes to 30 minutes for all users. The PPG Earring collected data at 50 Hz, which was later downsampled to 25 Hz to match the Fitbit sampling rate for comparison.

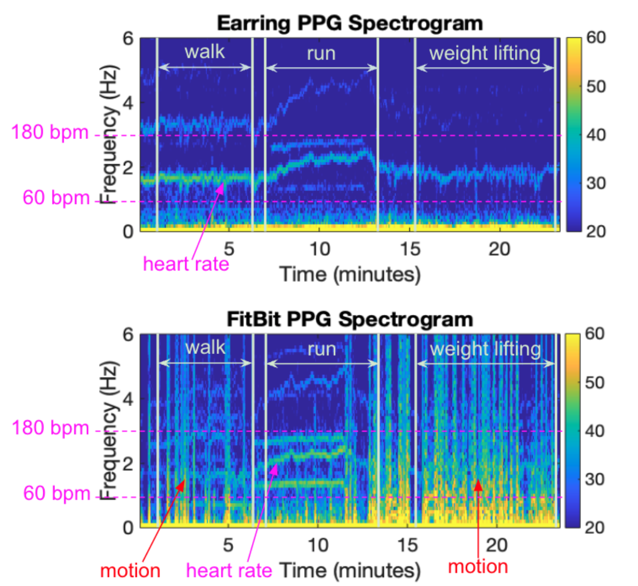


**Figure 10: (a) The spectrogram of PPG data from the earring during exercise. (b) The spectrogram of PPG data from the Fitbit during exercise.**

*6.2.1 Example participant's PPG results.* Figure 10 shows P1's spectrogram of PPG data from the earring versus from the Fitbit. The spectrogram was computed using the Short-Time Fourier Transform (STFT) with a window length of ten seconds and an overlap of five seconds. In Figure 10 (a), there is a clear continuous line from the start to the end in the heart rate frequency region (60 bpm to 180 bpm, which equals 1 Hz to 3 Hz). This line stands out distinctly against the background, representing the heart rate signal captured by the PPG Earring. We will validate this signal in a later section by comparing it to the Polar H10 chest strap, which serves as a reference.

In contrast, Figure 10 (b) shows the spectrogram from the Fitbit during exercise. As expected, the Fitbit PPG data is significantly affected by motion artifacts. Despite being worn tightly on the wrist, even small movements or muscle contractions in the hand still change the pressure between the wrist and the Fitbit sensor. These variations cause fluctuations or spikes in the reflected PPG light, which can overwhelm the subtle PPG signals, leading to inconsistent heart rate readings.

*6.2.2 Valid PPG percentage.* As discussed above, the PPG earring appears to be less likely affected by the motion artifacts during exercise and is still able to capture valid PPG data for computing heart rate. Figure 11 (a) shows the valid PPG signal percentage from earring versus Fitbit for each participant. The valid percentage of the PPG signal is defined in Section 5.

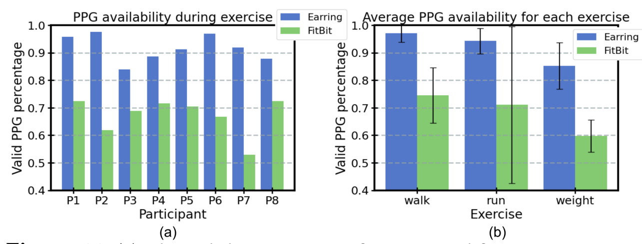


**Figure 11: (a) The valid percentage of PPG signal from PPG Earring and Fitbit for each participant during exercise. (b) The average valid percentage of PPG signal for each exercise.**

Figure 11 (a) shows the valid percentage of PPG signals from the Earring and Fitbit for each participant. Overall, PPG Earring captures valid PPG signals for more than 90% for six participants and 80% to 90% for two participants. On average, PPG Earring is able to capture 91.74 ± 4.84 % valid PPG signal during exercise for eight participants. In comparison, Fitbit captures valid PPG signals around 60% to 70% for most participants, except only 53% for P7. On average, Fitbit can only capture 67.16 ± 6.74 % valid PPG signal during exercise for eight participants. Though the Fitbit was worn on all participants not loosely, the natural contacting by the watch band does not guarantee constant pressure between the watch sensor and the skin, which can cause a lot of noise to the PPG signal. In addition, it should be noted that commercial Fitbit smartwatches might use a higher PPG light power than the earring, but we do not have access to the Fitbit PPG light setting.

Figure 11 (b) shows the average valid percentage of PPG signals for eight participants across different exercises. On average, PPG Earring achieves a valid PPG percentage of 97.03±3.13% for walking, 94.25 ± 4.63% for running, and 85.18 ± 8.46% for weight lifting. Fitbit achieves 74.55 ± 10.10% for walking, 71.05 ± 28.44% for running, and 59.71 ± 5.84% for weightlifting. It is expected that walking has the highest percentage of valid PPG for both the earring and the Fitbit since walking is the mildest activity here. Running is a more intense activity but PPG Earring still maintained a high quality signal of 94.25% with low variance. Fitbit shows a large variance in the capability of capturing PPG signals during running for different participants, likely due to people's different running

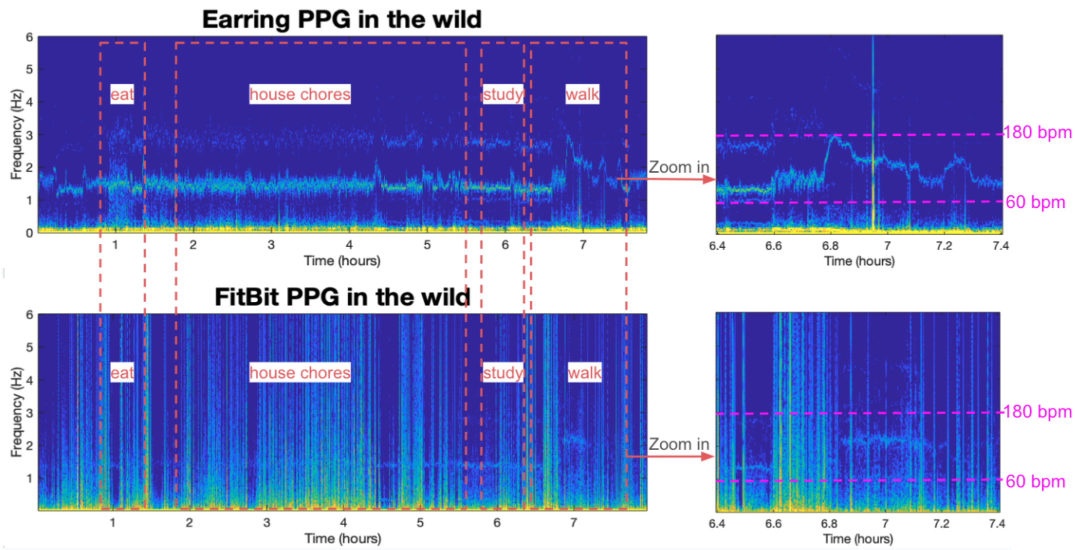


**Figure 12: The spectrogram of P6's eight hours of PPG data from PPG Earring compared to the Fitbit, along with a zoomed-in spectrogram of one hour of activity.**

patterns. In addition, Fitbit shows a low percentage of PPG signals during weightlifting for all users. This is expected since people use arm and hand muscles during weight lifting, which often change the contact pressure between the Fitbit sensor and wrist skin.

In summary, the exercise study results indicate that PPG Earring is more reliable for heart rate monitoring during exercise than the Fitbit and potentially other wrist-worn smartwatches, particularly during intense exercise with frequent movements or hand-involved activities.

## 7 In-the-wild Study

We recruited six participants to wear the PPG Earring and a commercial Fitbit smartwatch for a day (at least eight hours) during their normal daily routines. The participants included four females, one male, and one nonbinary individual, with an average age of 23.67 ± 3.27 years. Their skin tones ranged from Type I to Type IV on the Fitzpatrick scale. Participants were instructed to wear the PPG Earring (without decorative elements) and the Fitbit by themselves at a comfortable tightness. Some participants may wear the Fitbit more loosely than in the controlled exercise study. Each participant was provided an Android phone with the PPG Earring App to collect data, while the Fitbit data was stored locally on the device. They logged their activities in the Earring App throughout the day. At the end of the study, participants completed an online survey to rate the comfort of both devices and indicate their usual earring- and watch-wearing habits, including how frequently they wear these accessories in daily life.

### 7.1 PPG Earring vs. Fitbit smartwatch

Figure 12 presents the spectrograms of P6's eight-hour in-the-wild data collected from both the PPG Earring and the Fitbit. While the entire eight-hour spectrogram is dense and makes it difficult to observe rapid heart rate fluctuations over short time scales, we can still see general heart rate trends over the duration of the PPG Earring spectrogram, especially the increase in heart rate during periods of walking. The figure on the right provides a zoomed-in view of one hour of PPG data to provide details on the time scale, highlighting periods of both sitting and walking. Additionally, we observed that while the PPG Earring is generally less affected by daily motions, it is impacted by eating, specifically during chewing. This is likely due to the proximity of the earlobe to the jaw and facial muscles, where the movements during eating can cause motion artifacts.

When comparing the spectrogram results of the PPG Earring to those of the Fitbit, we noticed frequent vertical lines across all frequency ranges in the Fitbit spectrogram. These vertical lines are likely due to motion artifacts causing sudden changes in the PPG light path. The zoomed-in one-hour spectrogram of the Fitbit on the right shows that there are some short durations where valid heart rate signals are detectable and align well with the PPG Earring results despite the motion interference. Overall, Fitbit's data exhibited significantly more noise and motion artifacts than the PPG Earring data.

Figure 13 (a) shows the valid percentage of PPG signal for each participant in the study. One participant (P5) did not collect any data from either the PPG Earring or Fitbit, likely due to mishandling, and therefore, P5 is excluded from Figure 13. Across the remaining five participants, PPG Earring achieves an average valid PPG percentage of 86.29 ± 2.96%, while Fitbit achieves 54.88 ± 4.63% valid PPG. We observed that both devices recorded lower valid PPG percentages in the in-the-wild study compared to the exercise study. For PPG Earring, signal disruptions primarily occurred during self-reported eating periods, likely due to chewing or facial muscle movements introducing motion artifacts at the earlobe. This eating activity was present in every participant's data, contributing to the lower overall PPG availability in daily use. For Fitbit, the lower percentage was

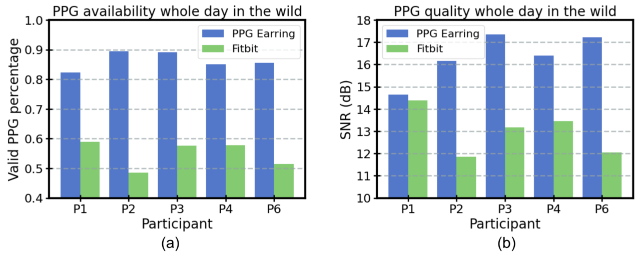


**Figure 13: (a) The percentage of valid PPG signal during the whole day in the wild study from PPG Earring vs. from Fitbit. (b) The average SNR of PPG during the whole day in the wild study from PPG Earring vs. from Fitbit.**

mainly due to participants wearing the device more loosely for comfort throughout the day, leading to increased motion artifacts.

Figure 13 (b) shows the computed average SNR for each participant. The SNR was computed based on the definition in Section 5, with an invalid PPG signal window being excluded from the SNR computation. On average, PPG Earring has an average SNR of 16.35 ± 1.09 dB during the in-the-wild study. And Fitbit PPG's average SNR is 12.98 ± 1.05 dB, which is significantly (3.4 dB) lower than PPG Earring.

## 7.2 PPG Earring Comfort Level Evaluation

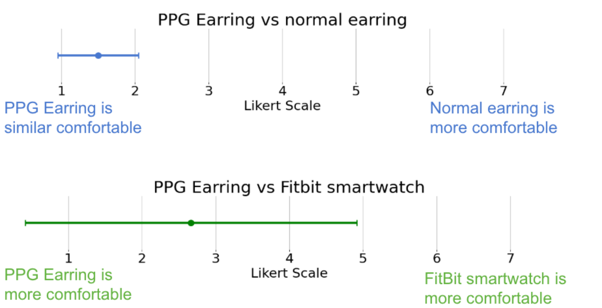


**Figure 14: The comfort level comparison of PPG Earring vs. normal earring, and PPG Earring vs. Fitbit smartwatch.**

After participants finished the in-the-wild study, we further asked them to complete a survey to assess the comfort of the PPG earring prototypes as well as their own earring-wearing habits. The survey evaluated the comfort of the PPG earrings during prolonged wear and compared it with that of the commercial Fitbit smartwatch and their daily earrings. The survey included both Likert scale ratings and open-ended questions to gather information on comfort levels for PPG earrings and Fitbit, participants' willingness to wear the PPG Earring or Fitbit daily, and the wearable comfort assessment for the PPG Earring and Fitbit [36].

*7.2.1 PPG Earring's Overall Comfort.* All six participants found the PPG Earring highly comfortable, with an average Likert rating of 1.33 ± 0.52 on a scale from 1 to 7 (where 1 means very comfortable). All participants found the PPG Earring was as comfortable as their normal earring: "***It was just as comfortable - I often forgot I had it on." (P3)***.

Most participants expressed strong willingness to wear the PPG Earring daily, with five rating their willingness highly (giving a score of 1 or 2) and one participant giving a moderate rating (giving a score of 3). For daily wear duration, five participants were willing to wear the PPG Earring for all day (12+ hours), while one participant preferred 7 hours due to skin sensitivity, as they only wore gold earrings for extended periods. Participants' willingness to wear the PPG earrings for extended hours suggests that it could be an attractive option for people already accustomed to wearing earrings. To further enhance user acceptance, PPG Earring's future designs could incorporate gold or other hypoallergenic materials.

*7.2.2 PPG Earring vs. Normal Earring.* The Figure 14 illustrates the comfort comparison of PPG earring vs. normal earring, and PPG Earring vs. Fitbit. All participants reported PPG earring to be as comfortable as their normal earrings. Three participants rated 1 on the Likert scale, and three participants rated 2 on the Likert scale (where 1 means PPG earring is as comfortable as normal earrings).

Three participants (P3, P4, P6) noted that they were not aware of the earrings' presence: P5 described the PPG earring as *"lighter than my normal ones"*, and P2 mentioned that the PPG earring felt like *"a regular earring with heavier stud or hoop."*

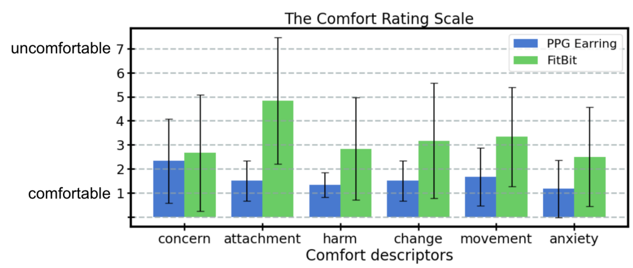


**Figure 15: The comfort rating scale results of PPG Earring and Fitbit on six comfort aspects of wearables.**

*7.2.3 PPG Earring vs. Fitbit Smartwatch.* Figure 14 shows the comfort preference of PPG Earring vs. Fitbit. The preference varied significantly across participants, with four participants finding PPG Earring much more comfortable (giving a score of 1 or 2) and two participants preferring Fitbit (giving a score of 5 or 6). While all participants expressed strong to moderate willingness to wear PPG Earring every day, they were less willing to wear the Fitbit daily, with four indicating unwillingness to wear the Fitbit smartwatch.

However, it should be noted that only three participants reported wearing smartwatches regularly (Garmin or Apple Watch), while all participants reported wearing their own earrings regularly, ranging from almost every day to every day. Among these three daily smartwatch users, two rated the Fitbit as more comfortable than the PPG Earring (giving a score of 5 or 6, where 1 indicates a strong preference for the earring and 7 indicates a strong preference for the smartwatch), even though both rated the PPG Earring as "very comfortable" overall (giving a score of 1). Additionally, one smartwatch user rated the PPG Earring as significantly more comfortable than the Fitbit (giving a score of 1) because they did not like the feeling of the silicone watch band.

Figure 15 displays the comfort rating scale results for the PPG earrings and Fitbit across 6 standard comfort descriptors for wearable computers [36]. We explain the six comfort descriptors here:

- **Concern**: Worries about appearance when wearing the device.
- **Attachment:** Awareness of device presence/movement.
- **Harm**: Feeling that the device may cause harm/pain.
- **Change**: Feeling physically different while wearing the device.
- **Movement**: Device restricting movement.
- **Anxiety:** Insecurity while wearing the device.

Overall, PPG Earring consistently scored lower (indicating more comfort) across all descriptors. Notably, it received significantly lower scores in the "attachment" category, with participants reporting they were less aware of the earring compared to the Fitbit, suggesting the PPG Earring may be less intrusive and more comfortable to wear.

Participants' qualitative feedback supported this finding. Half of the participants (P1, P4, P6) mentioned that the smartwatch felt bulky and interfered with daily activities: "*I didn't like how bulky watches are, they inhibit some movement.*" (P1). These findings suggest that the PPG Earring offers a more comfortable, lightweight alternative that minimizes the feeling of wearing a device.

# 8 Discussion

## 8.1 Fashion Design

To enhance the aesthetic appeal of the PPG Earring, we explored the design options for the earring. The primary structure of the PPG Earring features a circular battery at the front of the ear, with the system's PCB positioned at the back, connected by two wires. Since the PCB is discreetly placed behind the earlobe, the design focus is on the battery and the battery wires. Figure 1 (a) (b) shows an example fashion design we had on the battery. We recolored the battery with a layer of copper tape and attached a gold-plated lace pendant to the front of the battery. We also threaded 2mm diameter pearls onto the two wires to decorate the wires, making the PPG Earring look like a hoop earring. While this is just one example, the battery can be decorated with a range of fashionable elements commonly seen in stud earring designs. The wires can also be painted in various colors or wrapped with different materials to create unique textures and shapes, such as a twisted gold wires design. The fashion design of the PPG Earring is highly adaptable, allowing users to customize their look by swapping out decorative battery modules. This modular approach enables users to easily change styles, offering a variety of fashionable options for the PPG Earring system without affecting its functionality.

*8.1.1 Universal design.* In addition to swapping out the battery module, the PPG Earring could potentially be transformed into a universal earring back, with all components—including the battery—positioned behind the earlobe. This would allow users to wear any normal earrings of their choice and just replace their earring back as PPG Earring. This requires a customized battery shape with a central hole to let the earring post go through. This design presents additional challenges, as it limits the battery's thickness, thereby restricting the system's power capacity and requiring more efficient energy consumption.

## 8.2 Smart earring as a sensing platform

While this paper primarily evaluates the PPG Earring for heart rate monitoring, the device is capable of much more. It can measure heart rate variability (HRV), a key well-being indicator affected by stress, exercise, and sleep [63]. Since HRV is even more sensitive to motion artifacts than heart rate, smartwatches and rings typically only assess it opportunistically during stable periods, such as sleep [45]. In contrast, PPG Earring's motion-resilient design shows promise as a continuous HRV tracker, providing timely insights into users' well-being. Besides heart rate and HRV, the PPG Earring also measures SpO2, motion, and earlobe temperature, making it a comprehensive health monitoring platform. SpO2 readings reflect blood oxygen levels, and low levels may indicate respiratory or circulatory issues. The PPG Earring can alert users during these conditions and prompt timely medical attention. The motion sensor tracks steps and estimates calories burned during exercise, while the temperature sensor monitors earlobe temperature, enabling early fever detection and insights into menstrual cycles [72]. Although this paper focuses solely on PPG Earring's heart rate monitoring, we envision it as a general health platform for both users and researchers, providing a foundation for future earlobe-based monitoring of physiological signals, activities, and well-being.

## 8.3 Cardiac diseases detection

Since PPG Earring can sense valid PPG signals most of the time, the PPG signal can potentially be used to detect Atrial fibrillation (AFib) and other cardiac-related diseases such as loss of pulse. While PPG for AFib detection is actively being explored in the research domain, it is largely limited to strict still conditions because motions can cause a lot of false positives on smartwatch PPG [50]. Google recently introduced the loss of pulse detection using the PPG from Pixel watch [25], while the pixel watch requires a lot of algorithm processing to keep out the false positives of bad PPG signals, PPG earring can potentially achieve this with a better accuracy and simpler algorithm because of the natural of reliable PPG signal from the earlobe. In addition, most people wear two earrings, which can further reduce the false positive rate of cardiac disease detection.

## 8.4 Limitations and future work

Wearing the PPG Earring requires a pierced earlobe, which limits the target user group, as approximately 80% of women in the U.S. have pierced earlobes [65], while the percentage is significantly lower among men. While we have explored a magnet-based earring that does not require piercing, its performance was suboptimal due to increased susceptibility to motion artifacts and a higher likelihood of detachment during high-intensity movements. For the final design, we selected the pierced earring attachment due to its secure and consistent mechanical stability, which significantly improves signal quality. However, this choice also restricts the potential user base. In the future, a piercing-free, magnet-based earring could be an alternative if the overall weight of the PPG Earring system can be significantly reduced, allowing the magnets to hold the earring securely in place.

In this paper, we did not compare the PPG Earring's signal quality to a medical-grade heart rate monitor, such as an electrocardiogram (ECG), as PPG is a well-established and extensively studied technology. However, a clinical-grade study remains a crucial future step, particularly for cardiac disease detection applications.

PPG signal quality varies significantly based on skin color, with a well-known reduction in signal strength for darker skin tones [1]. We observed that IR light on the earlobe performs better for darker skin, while green light generally offers superior signal quality for lighter skin tones. This is likely due to IR light's ability to penetrate deeper into the skin and reach the blood vessels, whereas green light is more likely to be absorbed by darker skin. In future iterations, the PPG Earring could incorporate automatic adjustments to both light color and power settings, optimizing performance for different skin tones and environmental conditions.

In this paper, we only explored PPG Earring's usage during the daytime, instructing participants to remove it during sleep to avoid accidental damage. However, heart rate monitoring during sleep provides valuable insights into user's sleep quality. In the future, with more careful mechanical design and rigorous testing, the PPG earring could be adapted for use during sleep, enabling the collection of sleep quality data from the earlobe.

We observed that eating or chewing can cause significant noise on the PPG data on the earring, likely due to the jaw and facial muscle movement causing motion artifacts. While this movement interferes with PPG signal clarity, it could also be leveraged as a detection signal for eating behavior, allowing for monitoring of eating time and duration, which are important factors in overall health and wellness tracking.

While none of our participants reported issues with the PPG Earring's fit, individuals with significantly smaller than average earlobes ($19.6mm \times 18.8mm$) might find its $14mm$ diameter challenging to wear [12]. Future earring designs could be half the size through a double-layer PCB integration, accommodating potential users with very small earlobes.

## 9 Conclusion

We present PPG Earring, a smart earring for heart rate monitoring using PPG. PPG Earring measures 14 mm in diameter, weighs 2.0 g, and offers 21 hours of continuous PPG and motion sensing wirelessly. In experiments comparing PPG signal quality across earrings, rings, and watches under identical light settings, the earlobe provided 1.2 to 8.0 dB better signal quality than the wrist, and 0.2 to 3.3 dB better than the finger. We compared the PPG Earring's performance to a commercial Fitbit smartwatch in an exercise study and a whole-day in-the-wild study. The exercise study shows that PPG Earring captures valid heart rate data for $91.74 \pm 4.84$ % of the time during exercise, which is 24.5% higher than Fitbit. In our whole-da study, PPG Earring captured valid PPG for $86.29 \pm 2.96$% of time, which is 32% higher than Fitbit and has a 3.4 dB higher SNR. In addition, all participants in the in-the-wild study found the PPG Earring as comfortable as their regular earrings, and five out of six participants expressed a strong willingness to wear the PPG Earring all the time every day. Our study results not only validate PPG Earring's signal quality but also prove its comfort, highlighting its potential as a reliable daily health monitoring device.

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