Cardiovascular Monitoring Using Earphones and a Mobile Device

Many wearable biosensors have failed to be adopted outside of a lab setting or to gain popular acceptance. The Heartphones project seeks to address this by integrating physiological sensing capabilities into a platform already accepted for everyday use, exploiting sensor-embedded earphones and a smartphone.

Frequent and noninvasive cardiovascular monitoring is important in surveillance for cardiovascular catastrophes and treatment therapies of chronic disease. Resting heart rate, one of the simplest cardiovascular parameters, is an independent risk factor for cardiovascular disease (comparable with smoking, high blood cholesterol, or hypertension).\(^1\)

In particular, the association between accelerated resting heart rate and mortality has been observed in general populations, elderly subjects, and patients with hypertension, with coronary artery disease, or who have survived a heart attack. As such, long-term monitoring of resting heart rate has important prognostic implications and provides an index of efficiency of therapy.

Furthermore, regularly assessing bilateral circulation could help detect or monitor the progression of carotid artery disease (CAD), which is associated with increased risk of heart attack, ischemic stroke, and death from vascular causes. In particular, carotid artery stenosis often has no symptoms and is unknown to both the patient and doctor until it disrupts blood flow to the brain.\(^2\) Therefore, the development of wearable biosensors suitable for comfortable and continuous cardiovascular assessment could change the future of medicine by producing exquisitely detailed individual physiological data.\(^3\)

Despite significant advances in wearable technology in the past few years, wearable computers still struggle for social acceptance.\(^4,5\) To help address this issue, we developed Heartphones, a comfortable and socially acceptable system for measuring the bilateral blood volume pulse (BVP). The system fits inside ordinary earbuds to provide measurements such as heart rate and beat-to-beat changes in heart rate variability (HRV).

The Social Factor

A recent review of 25 state-of-the-art wearable systems for health monitoring revealed that many systems scored low in terms of aesthetics and wearability due to the bulky nature of sensors, batteries, and on-body hardware.\(^6\) Various form factors have been explored, including devices worn on the finger, forehead, wrist, and...
ear, but most of the proposed wearables still require connections to additional hardware pieces (for power or data acquisition) that are bulky and cumbersome. Ambulatory electrocardiogram (ECG) devices rely on chest straps or adhesive electrodes that can cause skin irritations and that people won’t generally wear outside of heart rate monitoring activity. This becomes a barrier for widespread adoption for daily use, because people don’t want to carry around a kit or additional gear. Furthermore, when people leave their home, they typically only remember to take a few items along with them.

To provide long-term and convenient cardiovascular monitoring, we must overcome significant technical challenges in terms of power, cost, size, weight, functionality, and packaging. Also, although it’s not often emphasized, there’s a social aspect to designing wearable computers and biosensors. The design and expense of a wearable computer not only reflect the user’s taste but also influence the wearer’s acceptance and opinion of the device.\(^7\) In general, people don’t want to look odd, so wearable biosensors should be designed to resemble a fashion item.

Instead of pushing for people to adopt a particular form factor, we address these challenges by observing what kind of electronic devices people will wear and carry. Mobile devices, such as cell phones and portable digital music players, are becoming increasingly widespread and offer significant computing power. At the end of 2008, the International Telecommunication Union estimated 4 billion mobile subscribers worldwide—more than half of the world’s population.\(^8\) Recent years have seen a rise in the popularity of smart devices such as Apple’s iPhone and iPod Touch. These are essentially powerful computers running full-scale operating systems, and as mainstream consumer devices, they have a form factor that’s widely accepted for everyday use. The white earphones that accompany these devices are popular and have become a fashion statement. Together, these present an attractive wearable platform for physiological sensing.

**The Heartphones System Design**

By adopting a smartphone as part of our platform, we exploit commonality in components such as microprocessors, computer memory, and the device’s screen, keyboard, and battery. This helps reduce the system’s cost and weight and eliminate redundancy. Instead of having to carry additional gear, Heartphones only need modified earphones and a cell phone—common pocket-size items.

**Sensor Earphones**

We designed the probes for Heartphones to resemble commercially popular intraconcha earphones, because such earphones are unobtrusive and have undergone extensive research to ensure a comfortable design. (See the “Related Work in Ear-Worn Devices” sidebar for more information on wearable cardiovascular sensors.) As Figure 1 shows, a reflective photosensor is embedded into each earbud on a pair of regular earphones. The reflective photosensor comprises an infrared LED that’s integrated with a phototransistor in a small resin package. Two diodes in series convert the changes in the collector current to a logarithmic voltage change to achieve a wide dynamic range of measurements (see Figure 1a).

To obtain measurements, the sensor earphones are inserted into the ear and positioned such that the reflective photosensor is against the inner side of the tragus (a small cartilaginous flap in front of the external opening of the ear). We can then measure the amount of light reflected from the subcutaneous blood vessels in the region; volumetric changes in the blood vessels during the cardiac cycle modify the path length of the incident light such that the subsequent changes in amount of reflected light indicate the timing of cardiovascular events. This technique of measuring the BVP is known as photoplethysmography (PPG). From the user’s standpoint, the sensor earphones look and work like a regular pair of earphones (Figure 1b), requiring no training or special effort to use.

**Processing Circuitry**

Figure 2 shows the system architecture of the integrated Heartphones system. The output signals from both the left and right earbud sensors pass through matched active bandpass filters (0.8 to 4.0 Hz) to separate the AC components and reduce electrical noise and motion artifacts. We matched the filters so we could detect true physiological differences when comparing the bilateral readings. We chose cutoff limits to reject noise and motion outside a reasonable heart rate range of 48 to 240 beats per minute (bpm). Note, however, that certain motion artifacts can also fall within this frequency range.

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These analog signals are then sampled at 400 Hz via an analog-to-digital converter with 12-bit resolution on a digital signal controller (DSC). We chose a sampling frequency of 400 Hz, because the recommended sampling rate for HRV measurements is above 250 Hz.\(^9\) The DSC acts as the control center that can be programmed...
Related Work in Ear-Worn Devices

Researchers have widely explored wearable cardiovascular sensors, and several ear-worn devices have been proposed. These systems commonly use photoplethysmography (PPG), a powerful sensing approach that’s especially suitable for wearable biosensors, owing to its low-cost and noninvasive means of sensing without the need for electrodes. This optical technique of measuring the blood volume pulse (BVP) that propagates throughout the body can provide valuable information about the cardiovascular system, such as heart rate, arterial blood oxygen saturation, blood pressure, cardiac output, and autonomic function.1

The Swiss Center for Electronics and Microtechnology introduced Pulsee,2 earcup headphones that contained sensors embedded in the horn and ear cushion for PPG measurements off the external ear cartilage. Similarly, the ear-worn activity recognition project3 proposed a sensor comprising an earhook with multichannel PPG recordings off the superior auricle. In the wearable in-ear measuring system project,4 researchers created a sensor-embedded otoplastic insertion that can be placed inside the auditory canal for PPG measurements.

A common drawback of all these systems is that they require connections to external units (for power, signal conditioning, and data acquisition) that are bulky; also, people don’t want to carry additional gear. More recently, a fully integrated, self-contained PPG earring and wireless headset was developed at MIT.5 However, the general population is dissatisfied with how the headsets look, and its usage is markedly declining in the US.6 Overall, current ear-worn platforms aren’t particularly convenient for pervasive physiological measurements or widespread adoption.

REFERENCES


Figure 1. Design of the sensor earphones. (a) A schematic of the sensor earphone with signal conditioning circuitry, and (b) a prototype of the sensor earphones, showing the embedded reflective photosensor.

on-board through an in-circuit serial programming interface.

We developed a simple PPG peak detection algorithm (Figure 3) that monitored the data in 90 ms segments and employed a variable amplitude threshold as well as a time threshold (minimum interbeat interval) to avoid false peak detections due to features in the waveform, such as the dicrotic notch (a secondary upstroke in the descending part of a pulse tracing). The system then sends the raw PPG waveform, each new detected beat interval, and the average heart rate over the last 30 beats to a mobile device (iPhone or iPod Touch) via serial communication for visualization or further processing. Alternatively, the system can also communicate wirelessly with a laptop using a pair of wireless 2.4 GHz radio transceivers modules.

When the control unit is connected to an iPhone or iPod Touch, it draws power directly from the device. A step-up/step-down charge pump produces a fixed, regulated output of 3.3 V for the DSC and peripheral components. Otherwise, the control unit operates on a single lithium polymer battery with a nominal voltage of 3.7 V that can be recharged on-board from a USB port. The entire control/processing module is 15 × 35 × 0.8 mm and fits into a compact
iPod connector housing, eliminating the need for a bulky external unit. Figure 4 shows the implemented system.

**Mobile Application**

We implemented a mobile application on an iPhone using custom software. The application lets users visualize their heart rate in real time by reading data from the DSC through the serial port. In addition, it keeps a record of the highest and lowest reading for that session. Users also have the option of viewing the raw PPG waveform and graphing their heart rate over time.

**Experiments and Results**

To demonstrate the capabilities of Heartphones, we characterized the accuracy of heart rate measurements and explored several application examples.

**Heart Rate Monitoring**

We designed Heartphones to promote pervasive physiological sensing. To evaluate our system’s accuracy in estimating a heart rate, we collected data from a total of 31 healthy participants between the ages of 18 and 47 (18 males and 13 females) during a series of experiments.

First, we asked participants to stand quietly for five minutes while wearing the sensor earphones along with three adhesive electrodes on their chest to record the reference ECG. Figure 5a shows a typical example of the BVP waveform measured by the Heartphones. The timing of the PPG waveforms was in close agreement with the reference ECG signal. For every QRS complex visible, there was a corresponding peak of the peripheral pulse that was clearly distinguishable. Figure 5b presents the differences between heart rate measurements obtained by Heartphones and ECG from 16 participants (304 pairs of 15 second epoch calculations) in a Bland-Altman plot. The red dotted lines in Figure 5c represent the 95 percent limits of agreement—that is, the boundaries within which we expect to find 95 percent of all differences between measurements (±1.96 standard deviation). Overall, Heartphones showed high agreement with ECG for heart rate measurements. The mean bias was −0.07 bpm, and the 95 percent limits of agreement were between −5.09 and 4.95 bpm.

In our subsequent experiments, we tested the performance of our system during physical activities. We asked 10 participants to sit quietly for two minutes on a recumbent bicycle and then cycle for five minutes followed by another two-minute period of rest. Figure 6a shows that for cycling (top), the BVP waveform during mild exercise remains clean, and the BVP peaks are still clearly discernable and synchronous with the QRS complexes from the ECG. Figure 6b (top) shows the dynamic variation in heart rate at rest and during cycling.
The heart rate that Heartphones estimated closely matched the ECG-derived heart rate throughout the experiment. As shown in the Bland-Altman plot for cycling (top of Figure 6c), the agreement between both measurements remained high. From 190 pairs of measurements, the mean bias was 0.67 bpm and the 95 percent limits of agreement were between –3.92 and 5.27 bpm.

Next, we asked the 10 participants to stand at rest on a treadmill for two minutes and then walk for five minutes (at 3.2 km per hour), followed by two minutes of standing at rest. The bottom of Figure 6a shows that the BVP waveform was occasionally corrupted but displayed high agreement with the ECG signal for the most part. The time course of the heart rate estimates during the experiments maintained close agreement with the ECG-derived heart rate (bottom of Figure 5b). From the Bland-Altman analysis of 190 pairs of measurements,
the mean bias was 0.51 bpm; for 95 percent of the measurements, the bias was between −9.89 and 10.90 bpm (bottom of Figure 6c).

Currently, our system already shows high agreement with ECG-derived heart rate measurements when users are standing (with a mean bias of −0.07, ±2.56 bpm), cycling (with a mean bias of 0.067, ±2.34 bpm), or walking (with a mean bias of 0.51, ±5.31 bpm). These results show that Heartphones provides robust measurements under conditions of moderate motion. Nonetheless, given that PPG is known to be susceptible to motion-induced signal corruption, it’s likely that device accuracy would decline under more vigorous activity. In particular, poorly fitted earbuds and motion of the earphone cables can introduce more sources of artifacts.

Under such conditions, motion-artifact removal techniques, such as adaptive noise cancellation, can be
applied to improve performance by incorporating accelerometers into the earbuds. We can also improve the accuracy using a longer epoch for calculations, such as one that covers at least 60 beats. Using shorter wavelengths of light (510 to 590 nm) increases sensitivity to the blood pulsations and will improve the signal-to-noise ratio. However, using IR light has its own advantages, because it’s not visible to the human eye.

**Music and Stress**

After integrating the sensors into the earphones, the earphones still retained their original function as audio output devices. To verify that playing music through the earphones didn’t interfere with the accuracy of measurements, we collected data from participants sitting at rest while listening to music. We tested a wide variety of musical genres, including classical, pop, rock, and hip-hop and found that music didn’t affect Heartphones’ performance.

Heartphones can measure a user’s stress levels and help regulate them with music by measuring HRV, an index of the cardiac autonomic nervous system activity that’s indicative of stress levels. PPG beat-to-beat variability can be affected by changes in the pulse transit time (related to arterial compliance and blood pressure), but it has been shown to be a good surrogate of HRV measured by ECG.

By monitoring HRV while music is played, Heartphones can help identify songs that aid in promoting relaxation and provide useful biofeedback to users. For example, using time-frequency analysis on the beat-to-beat intervals extracted from the BVP, we can observe the dynamic changes in HRV that show an increase in high-frequency power (0.15 to 0.4 Hz) while a participant listens to classical music (Figure 7). High-frequency power is driven by parasympathetic activity that promotes rest and restoration. Helping people relax during early signs of stress can modulate reactivity that could potentially damage their relationships and long-term health.

The ability to listen to music while simultaneously performing cardiovascular assessment provides a strong incentive for people to adopt Heartphones. Many people already listen to music while commuting, relaxing, studying, or working. Giving them the option of monitoring their heart rate and stress level with no extra effort promises to promote a healthier lifestyle.

**Bilateral Measurements for CAD**

Another potential application of Heartphones is in the area of continuous monitoring of carotid artery disease (CAD). Branches of the superficial temporal artery, which is a direct continuation of the external carotid artery, supply the tragus with blood. Moreover, simultaneous PPG measurements from anatomically symmetric sites of the body reveal important information about peripheral blood flow dynamics. Simultaneous bilateral measurements allow true physiological differences to be detected. Also, because bilateral measurements of supraorbital PPG have previously demonstrated clinical utility, Heartphones could potentially provide the same utility.

In our experiments, we obtained simultaneous bilateral PPG recordings from 15 participants (eight males and seven females) with no history of cardiovascular disease. We asked the participants to relax while seated for two minutes. To assess the similarities in the bilateral BVP waveforms, we calculated the cross correlation between left and right BVP signals for a normalized one-minute epoch that was free from movement artifacts. For each participant,
we obtained the Pearson’s correlation coefficient and the cross-correlation lag corresponding to maximum correlation. Figure 8a presents an example of simultaneous Heartphone BVP recordings from the tragi. The bilateral BVP recordings show good right-to-left symmetry with matching peripheral pulses. The mean correlation coefficient $r$ between the right and left recordings was 0.93 with a standard deviation of 0.04. The cross-correlation lag corresponding to the maximum correlation varied across the participants with a mean of 1.04 ms and a standard deviation of 17.25 ms.

As our results indicate, there’s high right-to-left symmetry and little difference in timing between bilateral PPG measurements obtained from healthy subjects with no history of cardiovascular disease. This is expected, because the anatomical structures are similar, and the autonomic nervous system innervates the peripheral vascular beds symmetrically on the right and left sides of the body. However, if there’s notable unilateral vascular narrowing or occlusion, as often occurs in the case of CAD, the vascular resistance would increase and the pulse wave would propagate more slowly.

Amplitude reduction, damping, as well as a pulse delay in the PPG waveform from the diseased side can occur with increasing severity of vascular disease, resulting in bilateral asymmetry. Heartphones could thus potentially aid in the detection of CAD. Also, 30 minutes of bilateral differential assessment while the user listens to music could provide daily monitoring to possibly detect exacerbations in early stages for timely intervention. A wearable platform for CAD monitoring makes patient empowerment and self-management possible and could help reduce the need for costly visits to the doctor’s office.

**Comfort Level**

Although there were differences in the quality of fit of the sensor earphones when placed in the ear, the earbuds stayed on during the experiments. All participants found the Heartphones to be comfortable and unobtrusive throughout the experiments (and many described it as “very cool”). When asked to compare the comfort level of the sensor earphones with a regular pair of earphones, they reported no difference between the two.

Perhaps more importantly, because there’s no obvious difference in appearance when a user wears the sensor earphones compared to regular earphones, this approach enables discreet monitoring. Nonstigmatizing cardiovascular assessment is important so that the wearer doesn’t need to feel awkward, uncoordinated, or concerned about his or her appearance. Based on this study, we expect Heartphones to increase user acceptance and patient compliance for regular monitoring. However, long-term comfort wasn’t specifically assessed in this study and must be considered in future studies.

This work advances previous research on wearable biosensors by presenting a convenient platform for cardiovascular monitoring that promises social acceptance and widespread adoption outside of the lab. Because devices such as the iPhone and iPod Touch tend to be very personal and carried wherever people go, Heartphones is a natural extension that adds the capability to track personal health.

Moreover, our system can be extended to measure other physiological parameters. For example, breathing rate can be calculated from the center
frequency of the high-frequency component in the HRV power spectrum. Embedding an additional red LED into the sensor earbuds would let us calculate arterial blood oxygen saturation. Future studies will investigate the use of Heartphones in screening patients for CAD and tracking chronic medical conditions.

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Selected CS articles and columns are also available for free at http://ComputingNow.computer.org.