Health Monitoring Based on Bone Conduction Headphones

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Abstract. With the continuous expansion of the headphone market size, headphones have already been combined with other functions, such as health monitoring and massage. In existing technology, air conduction headphones have already been linked with biosensors as a kind of in-ear device to monitor health. However, there are some problems when using this kind of headphones. There will be many discomforts when wearing this headphone for a long time. What is more, detected data will not be higher than out-ear device. Therefore, bone conduction headphones are proposed to be combined with biosensors for health monitoring for more comforts and higher accuracy. This article mainly compares existing device (in-ear device) with imagined device to verify the rationality of using bone conduction headphones. In addition, the principles of biosensors and anatomical mechanism are listed aiming to illustrate why there is more accurate data when using bone conduction headphones for health monitoring. A new kind of algorithm used for signal processing is also listed for eliminating external noise. Finally, a kind of bone conduction headphone which is combined with biosensors to monitor health is proposed. At the same time, the schematic diagram of sensor system that is composed of integrated sensor and integrated circuit is given. Then, the application scenario of this device is discussed and this headphone is advised to be applied in medical field and long-time monitoring field. Eventually, the perspective of materials is discussed to further improve the accuracy and comfort in the future.

Keywords: Bone conduction headphones, health monitoring, out-ear device, long-time wearing.

1. Introduction

In recent years, the headphone market has a broad prospect, which can not only be used to assist people with hearing loss, but also is widely used in medical field and daily life. For example, air conduction headphone has been applied as a substitute of electrocardiographic (ECG) to measure heart rate in combination with sensors. Thus, studying the combination of headphones and other equipment functions is capable of making people’s life more convenient. In the study of device for health monitoring, a kind of in-ear headphone was shown [1]. However, this device must be in close contact with the ear, causing discomfort in the ear and the occurrence of diseases of the ear canal. Research on the otomycosis in patients with cerumen impaction owing to headphone usage has mentioned that cerumen impaction will be caused when wearing headphones for a long time [2]. This kind of impaction is a major factor causing otomycosis. In addition, studies focusing on photoelectric pulse monitoring system has indicated that the biggest problems existing in the usage of photoelectric sensor for measuring data are measurement comfort and accuracy [3].

Research on the history of bone conduction headphones has revealed that the meaning of bone conduction headphone was first described in literature in the 1500s and credited to Girolamo Cardano [4]. This kind of headphone does not enter ears and conduct sound through bones, ensuring the comforts of our ears. Thus, it has no impacts on the conduction of external sound. It has been widely applied in medical field especially since COVID-19. During the period of COVID-19, doctors can not enter wards for safety reasons. This type of headphone is capable of achieving remote communication. At the same time, external information can also be conducted through ear canals, realizing simultaneous monitoring of information coming from different wards. Research on applications in hearing impairments limitations has revealed that it is potential to make a combination between bone conduction headphones and sensors, which has an application prospect in sports and fitness field, as well as medical monitoring and telemedicine [5]. This research is capable of making life more convenient and realizing health monitoring in long-time with more comforts.

This research is expected to realize the combination between bone conduction headphone and sensors. Except ensuring more comforts by using this kind of headphone, accuracy is also discussed from the perspectives of sensors, anatomical mechanism and signal processing. Taking these aspects into account, it is possible to realize higher accuracy. In this research, a previous kind of device (in-ear device) is discussed and some disadvantages are found. Then, a table showing the comparison between two kinds of devices is shown to verify the superiority of expected device. Eventually, for further improving comforts and accuracy, some advanced materials are referred and expected to be used in the future for making headphones. The final objective of this research is to realize a successful combination of bone conduction headphone and sensors to monitor health with higher accuracy and more comforts.

2. Method

2.1. Biosensors

Photoelectric biosensor can measure the intensity of reflected light by emitting a beam of light. PPG is a kind of photoelectric biosensor which have already been used to monitor health. In blood vessels, there are oxyhemoglobin and hemoglobin which are proteins and mainly absorb infrared light and red light respectively. In the photoelectric sensor, there will be a light source that will emit a beam of light which is composed of red and infrared lights. These lights will pass through tissues and reach blood vessels. They will be absorbed and reflected by proteins mentioned above. In addition to that, there will be a photo-detector that receives reflected light and transfer optical signals to electrical signals. The intensities of reflected lights are closely related to the number of these proteins. Blood oxygen saturation is the ratio of these two kinds of proteins and is an important signal that will be recorded by using photoelectric biosensor. From the ratio of the intensities of reflected lights (infrared light and red light), this biosensor can measure blood oxygen saturation. What is more, heart rate can also be measured by recording periodic intensity changes of reflected light.

Piezoelectric sensor can transfer perceived pressure changes to electrical signals. PZT (lead zirconate titanate) is a kind of piezoelectric materials that have been commonly used in sensor. Figure 1 shows the mechanisms of this kind of materials. Just like what is shown in this picture, PZT is a non-centrosymmetric crystal structure and has a net nonzero charge in each unit cell of the crystal before the application of mechanical stress. After applying stress, there is a shift in the position of the titanium ion inside the unit cell and electrical polarity develops. Therefore, the unit cell turns into an electric dipole. During systolic and diastolic phases of the heart, there will be different volumes of blood that pass through tissues. Thus, different blood pressure will be generated. By using piezoelectric biosensor, these pressure changes can be recorded and the heart rate value will be calculated.

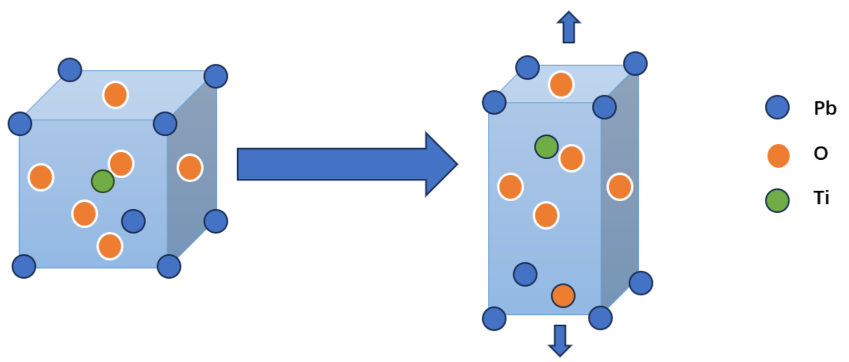

Figure 1. Mechanism of piezoelectricity sensor (PZT)

The reason why both of these biosensors are applied in headphones have been shown in previous research. The literature on bone conduction headphones suggests that the combination of these two kinds of biosensors can be accurate, non-invasive and low-cost [6]. When using photoelectric biosensor, in addition to the absorption of proteins in blood vessels, the absorption of other tissues is also what we should takes into account. Research on the usage of photoelectric biosensor for detection has found that signal attenuation is a common problem especially at high frequencies as the signal travels through soft tissue [4]. Furthermore, piezoelectric sensor detects by the vibration of the blood in veins. External noise is also a kind of vibration. When exercising, the collision between headphones and skin will also has effects on piezoelectric biosensor. Therefore, combining these sensors together, more accurate data can be got. Meanwhile, explorations of photoelectric biosensor has shown that PPG biosensors are passive transducers [6]. In other words, a power source is necessary to ensure that sensor is in operation. When power overload happens, higher temperature will be generated, making discomforts and having impacts on the accuracy of detected data. Research on piezoelectric sensor has also proven that PZT biosensor can act as an active transducer [6]. That is to say, power consumption can be reduced. In conclusion, from the perspective of principle of sensors, it is necessary to combine piezoelectric biosensor with photoelectric biosensor.

2.2. Anatomical mechanism

Research on the position used for placing sensors shows that ear canal can be used as an ideal site to monitor health [7]. The reason can be credited to the close position to the core of the body. Therefore, more accurate signal quality can be guaranteed. In addition, it is more suitable to get a fast response in different measurement situations because there is plenty of blood flowing there and less motion artifacts. Figure 2 is a picture showing the distribution of arteries around ears. There is an artery (superficial temporal artery) located between earlobe and the base of temporal bone. It is located superficially and the pulsation of this artery can be perceived by using hands. Thus, elements mentioned above like the absorption of other tissues can be eliminated. As a result of the obvious pulsation, piezoelectric sensor can get more accurate data. The most important element which induces a combination of bone conduction headphone with biosensor is that this artery has nearly the same position where bone conduction headphones are fixed. To be more specific, biosensors can be placed on this artery when using bone conduction headphones. This out-ear device will not only reduce discomforts in ears and the happens of ear diseases but also get more accurate data.

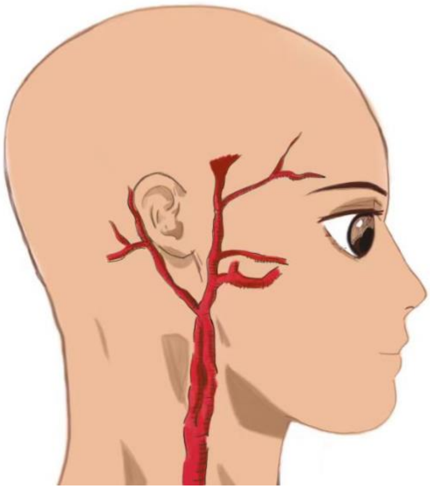

Figure 2. Arteries distribution around ears

2.3. Signal processing

In order to further improve the accuracy of detected data, signal processing is also taken into account except fixing the position of sensor, aiming to eliminate the impacts of motion artifact. Research on the algorithm used to deal with data has already linked heart rate sensing system with a kind of algorithm called dynamic detection algorithm (DDA) [8]. In this kind of algorithm, Fourier transform is used. It is a method that is capable of converting a time domain signal into a frequency domain signal. In frequency domain, a spectrum will be obtained as a polar coordinate (amplitude and phase) so the characteristics and properties of the signal can be better understood and the signal can be processed and analyzed. The algorithm used is called non-negative matrix factorization (NMF). NMF can decompose the spectral frequency data matrices into the product of two non-negative matrices which stand for basic frequencies and weights respectively. These matrices stand for different patterns in separate signals so useful information can be extracted by analyzing obtained matrices. Figure 3 shows these two matrices with the capital letter F and W respectively and the capital letter A stands for amplitudes obtained from Fourier transform. Figure 3 is a flow chart showing the principle of dynamic detection algorithm. Firstly, signals obtained by sensors is cut into several segments in STFT (short-time Fourier transform) and be presented as a polar coordinate (amplitude and phase). Then, these separate signals are transited to non-negative matrix factorization (NMF) Through this process, different signals are transformed into product of different matrices. Different signals are presented as A1, A2, A3 in Figure 3. The distinguishment of signals is achieved by deciding the number of calculations for pattern recognition. Obtained data will change with the number of calculations. Therefore, by analyzing the pattern of different matrices, it is successful to extract useful signal (heart rate) from motion artifact. Useful signal can be obtained by inverse short-time Fourier transform (ISTFT). Thus, the expectation that heart rate signal is detached from external noise is achieved. Research on the measurement by using commercial headphones has proven that this new kind of algorithm is capable of reducing the influence of motion artifact and getting more accurate data [8]. Despite the presence of ineffective noise interference, the required signal is strong. In other words, the signal separation between required signal (heart rate) and external signal has been achieved.

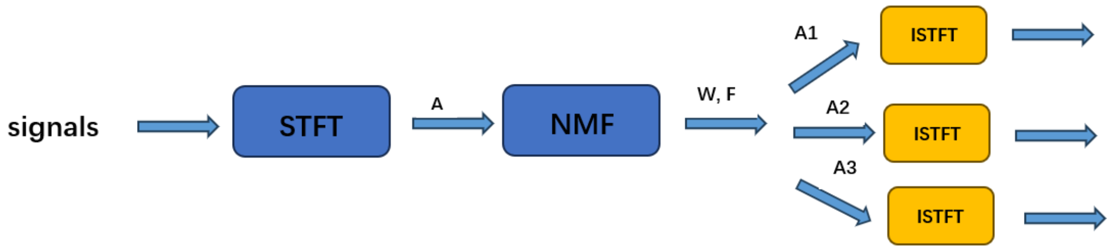

Figure 3. The principle of dynamic detection algorithm

3. Result

Figure 4 shows the integrated sensor and integrated circuit of imagined device. Bone conduction headphones have already been combined with biosensors and circuit to achieve the purpose of real-time monitoring. In Figure 4, it is shown that when signals are collected by piezoelectric and photoelectric sensors, they will firstly be processed by dynamic detection algorithm (DDA) to eliminate the impacts of motion artifact. After that, an amplification circuit is applied to increase the output of these signals. Subsequently, the signals will pass through analog to digital converter (ADC), microcontroller unit (MCU), digital to analog converter (DAC) in sequence. ADC will convert analog signals (pressure signal and optical signal) into digital signals. MCU will perform necessary calculations and analysis and obtained results will be transited into DAC. DAC will convert digital signals to analog signals. Finally, by connecting with Bluetooth, detected data (heart rate and blood oxygen saturation) is transmitted to a mobile app in real time.

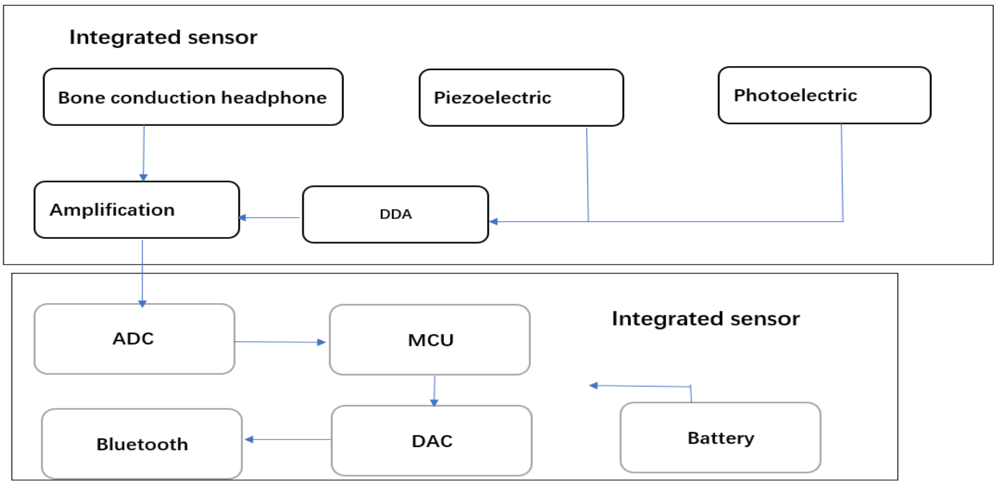

Figure 4. The principle of expected device

Research on the design of device used for monitoring health illustrates a kind of in-ear headphone which is used as a substitute of electrocardiographic (ECG) [1]. It has been shown that there is a bias of 0.78 bpm with a deviation of ±2.54 bpm compared with ECG. This comparison has shown high accuracy. However, this kind of device must have close contact with ear canal because biosensors are place in ears. Therefore, there must be a lot of discomforts when wearing headphones for a long time. In addition, though quality filtering is used to eliminate the impacts of motion artifact, the detected data is still affected by motion artifact.

Table 1 has shown the comparison between in-ear device and expected out-ear device. In out-ear device, piezoelectric sensor is also used to monitor health because of the obvious pulsation of artery. The biggest difference between these two kinds of headphones is the position of sensors. Out-ear device puts the biosensors out of ears while in-ear device fix PPG biosensor in ear canals, which must induce a difference of comforts. In-ear device also has the potential to cause ear canal diseases. Furthermore, quality filtering is used to eliminate the impacts of motion artifact while expected device applies digital detection algorithm to reduce the impacts. The extent of influence caused by motion artifact is also different. Thus, expected out-ear device has higher accuracy and more comforts compared with in-ear device.

Table 1. Comparison between in-ear device and out-ear device

	In-ear device	Out-ear device
sensor used	photoelectric sensor	piezoelectric sensor and photoelectric sensor
position of sensors	in ear canal	out of ears
method of signal processing	quality filtering	digital detection algorithm
whether affected by motion artifact	more	little
wearing comfort	lower	higher

Because of higher accuracy and more comforts, this expected device is more capable of continuous monitoring for clinical diseases such as arrhythmia and heart failure, respiratory illnesses like asthma, and sleep apnea. Additionally, in daily life, some activities like exercise can be long-time monitored. For example, this device can monitor exercise performance such as exercise intensity and calorie consumption by detecting the oxyhemoglobin saturation changing and send the information to APP which can calculate accuracy data and present it to the user. However, the materials used for making headphones and sensors have not been taken into account. It is also uncomfortable to wear this device when sleeping because the headphones are too heavy and hard, which will restrict its functions. In the future, the comfort and accuracy can be further improved by using advanced materials to solve this problem. The existing shell materials of headphones can basically be strong and durable, but their surfaces may be too hard, thus reducing the comfort. In the future, nano-materials such as carbon nanotubes and some flexible materials are considered to be used to reduce the weight and stiffness of this device to improve the comfort of wearing. In addition, the weight and stiffness can also be reduced from the aspect of headphone circuit. Now, most of the headphone circuit is made of metals, such as copper and silver. These circuit materials have already met the requirements of electrical conduction. But they may add weight. In the future, graphene and miniature integrated circuit technology will be used, thereby reducing weight and volume. There is plenty of promise when using CNT (carbon nanotube)-based cables. Research on the structure of CNT has revealed that CNT has the nature of hollow cylindrical, inducing lower mass density [9]. What is more, CNT has better electrical conductivity than cooper. Research on the measurement about headphone frequency response between commercial headphones made of cooper cables and headphones equipped with CNT/Cu cables has shown that there is nearly no difference, demonstrating the CNT/Cu cables are an excellent alternative to commercial copper cables [9]. In addition, more advanced and transparent optical materials are expected to be used to enhance the light transmission ability and reduce the scattering loss, thus improving the sensitivity of the sensor. Research on the materials used in the production of sensors illustrates a kind of materials called anisotropic 2D materials can be used as photodetector [10]. This kind of materials has unique crystal structure and can not only distinguish intensity but also the polarization direction of light. It can be used as better optical materials in photoelectric sensor.

4. Conclusion

The expected device has the advantages of improving skin-friendly feeling and relatively improving the accuracy of the measured data. It compensates for the disadvantages (discomforts, lower accuracy) existing in in-ear device. By the schematic diagram of sensor system listed above, it is greatly possible to achieve the goal of real-time health monitoring. At the same time, because bone conduction headphones do not have impacts on the conduction of sound through ear canals, it can be used when exercising to eliminate the risk on roads. Used in medical field, multiple monitoring for patients is possible. Most of important of all, the duration of wearing headphones will not affect the comforts of ears, realizing long-time monitoring. It can also be used when sleeping to monitor the state of body. Some diseases like asthma and sleep apnea can be detected and transited into APP in time. This research mainly compensates for the deficiency of using headphones for long-time monitoring. It enables people to obtain real-time information which has higher accuracy than previous device concerning health. Simultaneously, people will not feel uncomfortable when wearing for a long time. It can be seen as a substitute of medical equipment which is used to monitor health. However, existing research does not consider the materials used to make this device, which will enhance the weight and stiffness of expected device. It is hopeful to apply flexible materials to the production of this device in the future to solve the problem of weight and stiffness. Therefore, it is convenient to use the device when sleeping.

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