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Feasibility study on the potential of using polarization as a means for filtering to increase the dynamic range of optical sensing on the ear for the analysis of physiological phenomena *

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***Abstract*— The use of changes in polarization orientation resulting from tissue structure as a means of optical filtering with respect to ambient light was investigated. The sensing mechanism currently used by Valencell, Inc. uses a light-source to provide optical sensing of biometric and physiological values directly underneath facilitated by an adjacent sensor. This mechanism of action is subject to distortion noise and off-set background resulting from both sunlight and ambient-light. Based on prior work the potential of the birefringence of striated tissue that will selectively transmit light of certain polarization directions was considered as a tool for partially blocking the light. At this point in the study there is no supporting evidence, either optically or histologically that will provide a mechanism for filtering ambient light based on polarization orientation using the potential birefringent properties of the tissues of the ear while measuring with the Valencell earbud device placed on the ear.**

I. Introduction

Valencell, Inc. utilizes the optical properties of blood versus tissue in the ear to measure and collect biometric and physiological data. Time dependent changes in optical attenuation of light, resulting from physiological phenomenon, allow users to obtain real time fitness data. A custom probing device containing a light source is placed in contact with the skin of the outer ear in the helix of the concha. The light propagates through the tissues of the ear, where it interacts with steady-state tissue and dynamically changing blood-flow. The light is both scattered and attenuated based on the respective optical properties of all tissues encountered.

The Valencell device relies on the light that is backscattered from the bulk tissue and blood vessels located directly below the light source. The collected light resulting from backscatter can be used to provide information on the optical properties of tissue underneath the light-source and detector. Changes in optical characteristics of the tissue can be used to identify periodic phenomena, such as heart rate, and respiration as well as relative or absolute blood-oxygenation.

The device technology developed by Valencell senses seveal biometric values including but not limited to heart rate, respiration rate, R-R interval, energy expenditure, Calories burned, distance traveled, steps taken (cadence), speed, ventilatory threshold, as well as recovery time, metabolic rate and cardiovascular fitness (VO_2 max). Heart rate can be measured using the concepts of systolic and diastolic blood flow. During respiration, the blood flowing through the lungs is saturated by oxygen, forming oxyhemoglobin. The blood is then pumped by the heart into circulation throughout the entire body. During systole, the heart contracts and pumps blood into the arterial system, resulting in localized vascular expansion to mitigate the sudden excess of blood volume. During diastole, the heart muscle relaxes and flow subsides, resulting in a decrease in local blood volume. The investigation of a sensing mechanism that is virtually impervious to external conditions directly underwrites the development of wearable monitoring devices targeting recreational exercise enthusiasts in addition to professional and amateur athletes.

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II. Background

A. Motivation

Optical sensing is prone to a variety of noise and background factors that need to be mitigated for increased sensitivity and accuracy. Next to signal processing efforts and the use of ambient light sensors, additional background reducing mechanisms need to be investigated for value while compliant with the wearable device platform. The primary requirement of small device size with accurate detection limits the options available for limiting external influences.

Focusing on the properties of light, polarization may offer a mechanism for discrimination and reduction in background.

B. Mechanism of Action

Blood has different optical properties than fat, muscle, and surrounding connective tissue [1]. The time-varying optical attenuation of blood is generally greater than the time-varying optical attenuation of bulk tissue in the visible and infrared spectrum of light. During systole, the volume of blood in vessels increases relative to steady state, resulting in greater attenuation [2]. The more oxygenated blood an artery contains, the more attenuated the light becomes. Because attenuation increases during systolic blood flow, less light is backscattered. During diastolic blood flow, the heart relaxes and there is less oxygenated blood in the tissue volume under interrogation by the optical probe, resulting in a relative decrease in attenuation resulting from the blood [3.4]. Due to the pulsating nature of blood flow, the volume of blood changes over time between systolic and diastolic flow. This continuous change in volume results in changes in

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attenuation and scattering of light. Additionally, the attenuation of blood changes with oxygen concentration. Oxygen is used by the muscles and tissues of the body in an effort to maintain metabolic homeostasis.

The pulsatile phenomenon probed with two or more specific wavelengths provides the platform for pulse-oximetry.

C. Why is this important

The Valencell device uses near infrared radiation to probe the tissue for optical characterization. Due to the specific wavelength range of the electromagnetic spectrum that the device utilizes, as well as its sensitivity, other types of radiation can influence its optical measurements [5-13]. Sunlight, as well as any indoor ambient light, interferes with the accuracy of the measurements taken using a designated light-source. All light is collected by the light detector without discrimination for origin. The purpose of the photocell is to measure only light backscattered from the biological medium illuminated by the probing light source, which has specific emission spectrum characteristics. Therefore, any background light that does not come from the light source must be eliminated in order to ensure sensing and diagnostic correctness. In addition, the signal from the inherent light source in the sensing device is small, especially compared to sunlight, specifically infrared radiation.

In addition to several mechanisms already in place to reduce the background influences such as signal processing there is a persistent interest in enriching the signal quality. The retrieval of vital and sometimes concealed amplitude and frequency modulation events resulting from physiological phenomena remains a challenge.

D. Hypothesis

Based on various experimental observations involving striated tissue, the general assumption is that the fiber orientation of both muscle and certain types of collagen can affect the transmission of polarized light [14-17]. For instance, during histological examination, the potential birefringence of tissue can be used to discriminate between certain tissue structures based on the filtered polarization orientation of the transmitted source light. Specifically, striated tissues such as muscle and certain types of collagen offer effective discriminant mechanisms. In the case of striated structure, it may influence the polarization of ambient light when transmitted through the external ear. This transmitted light can potentially be eliminated by placement of a polarizer in front of the light detector at a 90 degree angle to the collagen orientation. In such case, the earbud optics may be designed to incorporate a polarization filter that would substantially attenuate sunlight noise but only moderately attenuate the desired photoplethysmography signal. From an ergonomic standpoint, placement of the polarization filter on the sensor within the earbud would be a desirable solution.

The purpose of this experiment was to determine the potential of blocking ambient light through tissue using the polarization altering effects resulting from the structure of collagen fiber in the ear. In theory, this filter would partially block the transmission of light from reaching the detector in the sensing device, which is placed in the concha of the ear as illustrated in Figure 1.

III. MATERIALS AND METHODS

Human cadaver ears were used to measure optical transmission through the helix of the concha of the external ear. All measurements were performed under IRB approved protocol in the tissue laboratory of the department of Biomedical Engineering at North Carolina State University (NCSU, Raleigh, NC, USA). Human ears were obtained post mortem from a licensed dealer (Human Focused Testing, Cambridge, UK).

Figure 1. Example of the optical placement of the Valencell earbud integrated with physiological sensing using optical source and detector while exercising.

Feasibility studies to determine the influence of tissue on the detected polarization orientation of the combination of transmitted ambient and backscattered sensing light were initially performed on the tissue of 3 ears. Ears were numbered according to order of acquisition: #1; #2 and #3 respectively. In case the feasibility was validated additional test with a large statistical pool were scheduled. Due to the limited available time on the project the feasibility study was confined to a limited scope. Additional tests could identify interpersonal variability in the histology of the tissue structure and the associated optical variability, as well as ascertain location sensitive inconsistencies. A total of three right ears were used for testing from diverse racial and gender backgrounds. The ears were stored in cold (ca. 4 ^0C) saline solution during shipment in order to preserve the tissue from degradation. Measurements were taken less than 24 hours post-mortem. It was important to take these measurements as soon as possible before any of the tissue began to decompose, which would have affected the optical characteristics and hence the accuracy of the measurements.

A photocell (BPW34; Siemens, Germany) with a polarizer (Edmund Optics, Barrington, NJ 08007, USA) placed in front, as illustrated in Figure 2, was used to determine the light transmission through the concha of the ear as a function of polarization angle. The spectral sensitivity of the photocell has a maximum at 920 nm and drops off rapidly with increasing wavelength.

A. Measurements

The light transmitted through the ear was measured with the external polarizer rotated at 15 degree intervals. The 15 degree increments are intended as a rough gauge that can be sub-divided in 5 degree intervals to identify the exact orientation of preferred polarization in case a trend is recognized in transmission as a function of angle.

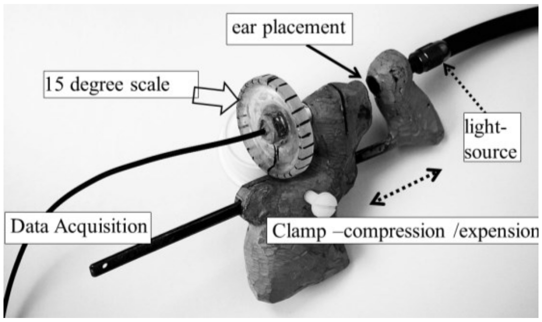

Figure 2. Earclamp with polarizer and angular positing dial on the proximal side and the opening on the opposite distal side is fitted with a probe-tip (dash-arrow) of the liquid light-guide transmitting light from the broad-band light-source. The ear is placed in the void indicated by the black arrow and the detector and light-source are clamped together firmly holding the ear in place during the rotation of the polarizer indicated by the outlined arrow. The black cable leads to the electronics data acquisition unit.

A light source coupled to a liquid light-guide (Quadrilite 4000 Universal Light Source, Designs for Vision, Ronkonkoma, NY 11779, USA), which has a power output of several milliWatt, was used to direct a ray of light through the ear. The light-source emits visible and infrared light in a virtually homogeneous spectral output over the wavelength range of interest; consistent emission profile from 500nm to 1800nm. This signal was collected by a photocell, or light detector, which converted the light into electricity. The magnitude of the signal output was measured using a voltmeter. Light transmission measurements were taken at three separate locations in the concha of the ear. All transmission measurements were made in the thin section of the concha of the outer-ear concha the light passing through the tissue anatomy in a direction perceived parallel to the skull. The total thickness of the portion of the area of interest in the ear is on average 5±1 mm in this area. The section at the lobule can range in thickness quite dramatically depending on the location of attachment and anatomical form-factor with respect to the skull. The thickness of the lobule itself ranges on average from 10 mm to 40 mm, with a variety of structural features.

A diagram of the ear detailing the locations of interest is shown in Figure 3. Location 1 is at the lobule under the antitragus (vertical, parallel to the skull), location 2 is at 45^0 in the antihelix, and location 3 is in the antihelix at horizontal orientation, all with the light-path parallel to the skull, transmitted through the thinnest section of the ear-tissue.

In order to determine whether light transmission was blocked by a polarizing effect due to the collagen structure, the polarizer was rotated 15 degrees for each measurement. A minimum of two measurements per angular position was performed at each location. This procedure was repeated at each location within the ear. Unless there were significant discrepancies between measurements no additional measurements were executed.

IV. Results

In order to ensure that the same area of tissue was analyzed for each angle of polarization, the polarizer was rotated as opposed to rotating the ear. There was no discrepancy in data due to the fact that the location of the light-source and detector, respectively, with respect to the ear tissue was unaffected by the rotation of the polarizer between measurements. According to an article by Xiaohong Bi on the Fourier transform infrared imaging spectroscopy, a comparison of amide ratios confirms that rotating the polarizer is identical to rotation of the tissue region while holding the polarizer constant [15].

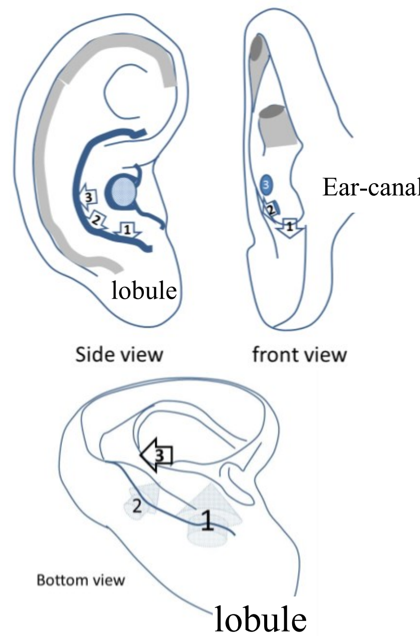

Figure 3. Diagram of ear and the measurement locations.

The measurements of polarization-sensitive light transmission taken at 3 different locations within the concha of the ear were similar for all locations. The polarization filter is placed in front of the sensor and was rotated in incremental steps of 15 degrees clockwise as well as counterclockwise over 360^0 to investigate the angle of polarization of transmitted light after passing through the collagen fibers of the ear before reaching the detector, resulting from the irradiation by unpolarized light. The representative average results for all ears are represented by the recordings at location 1 shown in Figure 4. Location 1 is defined at the bottom of the concha. A graph in Figure 4 illustrates the relationship between light-transmission with respect to polarization filter orientation angle of polarization. Virtually identical results were obtained for the respective locations on the ear as indicated by Figure 3 as well as under repeated exposure for all three ears.

Upon closer examination of the histology of the ear it was found that the collagen of the ear consists mainly of type I and II. Collagen I has a tendency to be discretely organized with no uniform structure supporting an aligned optical activity and as such only localized birefringence [18,19].

Collagen II is also not organized or striated [20] and as such no persistent birefringence would be expected from these two types of collagen and hence no specific influence on the polarization of transmitted light would be expected. The gross anatomy of a cross-section of the concha of the ear is illustrated in Figure 5.

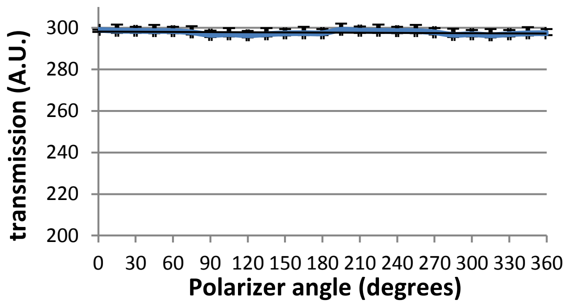

Figure 4. Average and scaled data at location 1 in the ear illustrating light transmission measurement at the relative angle of polarization with respect to horizontal.

Figure 5. Gross anatomy of the ear at horizontal cross-section. The helix of the concha is on the left, corresponding to location "3".

V. Conclusions

The collagen in the concha of the ear does not appear to provide a significant degree of selective blockage of polarized light that may provide additional filtering opportunities for optical sensing. No additional ears were investigated due to the perceived consistent transmission pattern.

The hypothesis was refuted and no optical characteristics that can benefit the signal-to-noise ratio were revealed.

The reaffirmation of the minor influence on polarization warrants the investigation of additional opportunities. Additional research is in progress to investigate the anatomical tissue structure of the concha of the ear, specifically related to the presence or (lack-off) abundance of striation in the collagen structure as a function of location. The histological information on the structure of the collagen fibers of the ear will provide insight into whether or not the ear has a defined collagen network. Furthermore the anatomical information can shed light on the fact whether these fibers have the potential to provide birefringent characteristics based on the structure and density as well as tissue-grouping.

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