Transdermal Optical Imaging Reveal Basal Stress via Heart Rate Variability Analysis: A Novel Methodology Comparable to Electrocardiography

by

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Abstract

The present study examined the validity of a novel physiological measurement technology called transdermal optical imaging (TOI) technology at assessing basal stress. This technology conveniently, contactlessly, and remotely measures facial blood flow changes using a conventional digital video camera. We compared data from TOI against the pulse data collected from the FDA approved BIOPAC system. One hundred thirty-six healthy adults participated in the study. We found that TOI measurements of heart rate and heart rate variability, which reflects basal stress, corresponded strongly to those obtained from BIOPAC. These findings indicate that transdermal optical imaging technology is a viable method to monitor heart rate and heart rate variability not only accurately but also conveniently, contactlessly, and remotely. Further, measures of heart rate variability obtained via transdermal optical imaging serves as a valid index of basal stress. Potential applications of this technology in psychological research and other fields are discussed.

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Chapter 1

1 Introduction

Humans encounter various stressful situations everyday at work, home, and school. Such stress when experienced at high degrees and/or for a long duration of time could lead to cardiovascular diseases, cognitive dysfunctions, and psychological disorders (Kofman, Meiran, Greenberg, Balas, & Cohen, 2006; Crowley et al., 2011; Pan & Li, 2007). Currently, the assessment of stress relies on the analysis of psychometric (e.g., self-report to interview or questionnaires) and/or biometric (e.g., saliva samples, electrocardiography) data. While psychometric data can provide a glimpse into an individual's psychological state and stress level, it is heavily dependent upon a subjective reflection of events and conditions. On the other hand, biometric data can provide an objective evaluation of physiological activity that has been demonstrated to correlate well with psychological stress (Sharpley, & Gordon, 1999; Tavel, 2001). However, biometric data are often obtained using instruments which require contact with the body by trained individuals, whether for the purposes of extracting specimen or for the attachment of electrodes or sensors. This use of physiological measurement instruments can be inconvenient. Thus, to date, we still face difficulties in monitoring stress levels both reliably and conveniently. The present research aimed to address these difficulties directly.

1.1 Stress based on Heart Rate Variability (HRV)

Over the last half century, research has revealed that human physiological changes in response to psychological stress, such as the amplitude of respiratory sinus arrhythmia, can reflect individual stress (Porges, 1995). When individuals encounter a stressful situation where a threat is perceived, their autonomic nervous system (ANS) works to adjust the internal state of their body and react to the situation. The two branches of ANS, the sympathetic and parasympathetic nervous systems, contribute in stress reaction. The sympathetic nervous system is concerned with challenges from the external environment, triggering the fight-or-flight response in stressful situations. In contrast, the parasympathetic nervous system is concerned with returning the body to a resting state or the state of homeostasis. When an individual experiences stress, the parasympathetic nervous system struggles to maintain homeostasis (Porges, 1995). Thus, an assessment of stress can be obtained by examining the level of homeostasis.

As part of the parasympathetic nervous system, the vagus nerve plays an essential role in the regulation of homeostasis because it is responsible for signaling the heart, lungs, and digestive tract to slow down and relax. The activity of the vagus nerve, otherwise known as vagal tone, would then be indicative of the level of homeostasis within the body. If individual stress decreases, then vagal tone increases, the heart slows down, and homeostasis is maintained. If individual stress increases, then vagal tone decreases, the heart quickens, and homeostasis is disrupted.

Although vagal tone can provide insight into an individual's stress level, the changes in vagal tone cannot be measured directly. Rather, vagal tone and corresponding information involving stress can be measured indirectly but reliably by respiratory sinus arrhythmia (RSA). RSA is the rhythmic increase and decrease in the beating of the heart, which occurs in the presence of breathing (Berntson et al., 1997). The heart rate increases with inhalation and decreases with exhalation. Studies have shown that a decrease in resting RSA is indicative of increased stress (Friedman, 2007; Jonsson, 2007; Kemp et al., 2010; Watkins, Grossman, Krishnan, & Sherwood, 1998; Kogan, Allen, & Weihs, 2012).

In order to obtain a measurement of RSA, variations in heartbeat must first be measured. Experimental evidence primarily relies on the use of ECG to observe HRV, analyzing the time period in milliseconds between each R-wave to obtain the R-R Interval (RRI). With information regarding the RRI, inferences can be made about stress. An increasing RRI variation indicates excitation of the vagus nerve as it works to decrease heart rate, and thus we can infer stress level to be low. A decreasing RRI variation indicates an inhibited vagus nerve, allowing heart rate to increase, and thus we can infer stress level to be high (Castaldo et al., 2015; Castaldo et al., 2016). However, assessment of RRI is not enough to determine vagal tone. The issue is that respiration is not the only contributor to variations in heart rate. There are oscillations at frequencies slower than that of respiration, such as Traube-Hering-Mayer waves, which provides information regarding the sympathetic nervous system rather than the parasympathetic nervous system and stress (Porges, 1986). Thus, data from ECG recordings must be filtered to obtain various heart rate variability (HRV) features for the purposes of observing individual stress levels. This has been further instantiated by a recent review of research by Castaldo et al. (2015), showing that parasympathetic vagal activity, as determined by heart rate variability (HRV) time series computed from electrocardiography (ECG) recordings, indeed decreases reliably during

sessions involving stress. In addition, irregular increase and decrease of vagal tone would indicate chronic stress.

1.2 Transdermal Optical Imaging (TOI)

Based on the evidences of cardiovascular changes in response to stress, we have specifically developed a new imaging technology called Transdermal Optical Imaging (TOI) to assess stress conveniently, contactlessly, and remotely. This technology uses a conventional digital camera to video record participants' faces from a distance, analyzing facial blood flow information to obtain participants' heart rate and HRV.

Our TOI technology is built upon a century of research that has revealed cardiovascular activities to be obtainable via analyses of blood flow changes. It is well established that light can travel beneath the skin and re-emit due to the translucent property of the skin (Brunsting & Sheard, 1929; Dawson et al., 1980; Edwards & Duntley, 1939). Furthermore, this re-emitted light can be captured by an optical sensor, from which blood flow information can be obtained (Anderson, 1991; Demirli, Otto, Viswanathan, Patwardhan, & Larkey, 2007; Stamatas, Zmudzka, Kollias, & Beer, 2004). Information regarding blood flow changes reveal cardiovascular changes given that movement of blood from the heart to the rest of the body is part of the cardiovascular system. These discoveries have lead to the development of various methodologies (e.g., laser Doppler flowmetry, photoplethysmography) that measure cardiovascular activities optically. However, similar to the utilization of electrocardiography, these methodologies require the attachment of sensors to the body, which can be inconvenient.

TOI overcomes the limitations of current methodologies by utilizing a CCD video camera to conveniently, contactlessly, and remotely capture video images of the face for extraction of cardiovascular changes. This is possible because re-emitted light from underneath the skin is affected by chromophores, primarily hemoglobin and melanin (Nishidate, Aizu, & Mishina, 2004), which have different color signatures. Given the difference in the color signatures, we can use machine learning to separate images of hemoglobin-rich regions from melanin-rich regions, ultimately obtaining video images of hemoglobin changes under the skin (Figure 1; for details, see Lee & Zheng, 2016). The face is ideal for analysis of blood flow changes because it is rich in vasculature and exposed, allowing us to obtain blood flow information conveniently, contactlessly, and remotely.

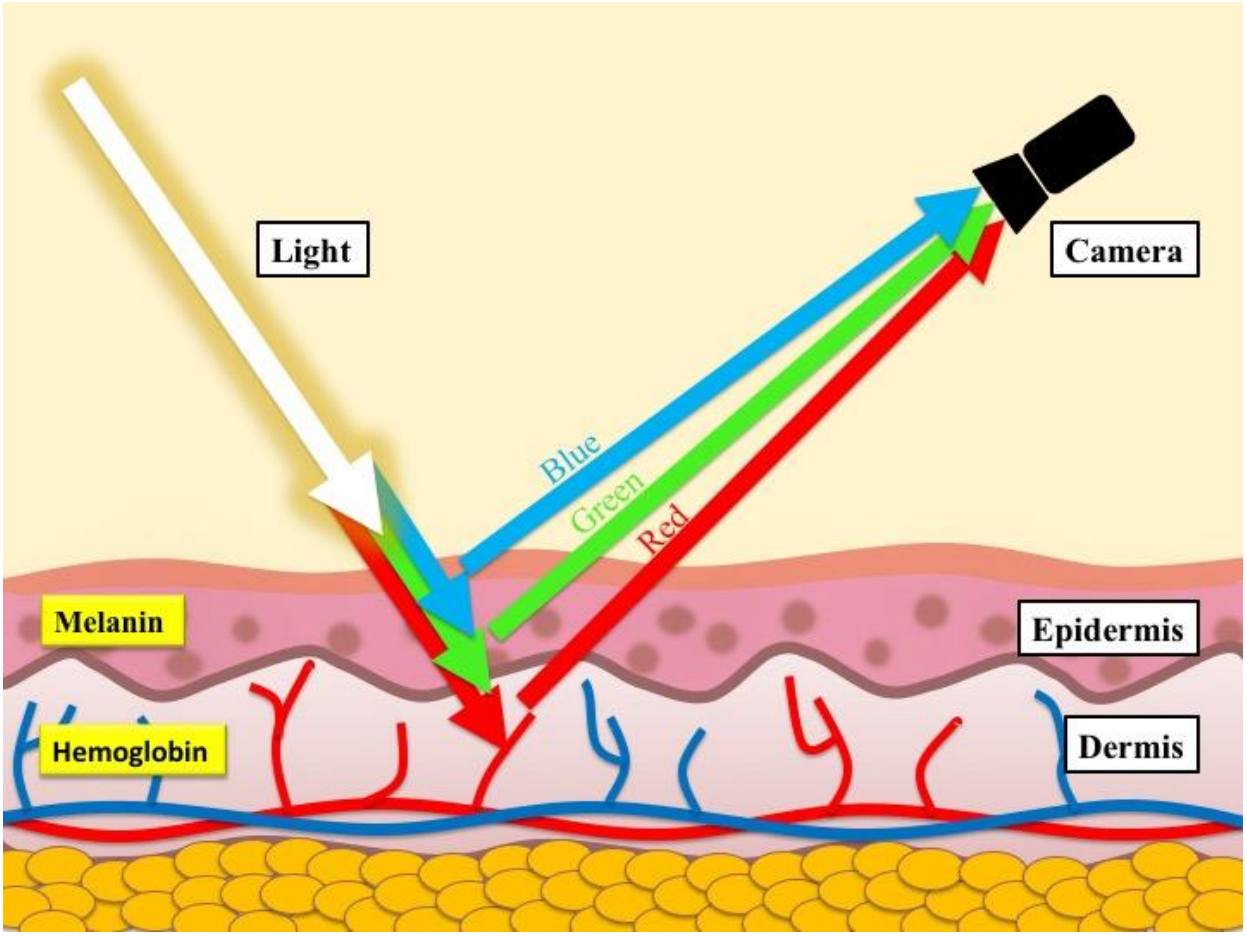


Figure 1. Illustration of the skin structure and the skin color model.

1.3 The Current Study

In the present study, we examined the validity of TOI in measuring heart rate and HRV, which reflects individual stress. We measured participants' cardiovascular activities while they were in a state of rest to assess their basal stress levels. We used the TOI methodology to obtain facial blood flow data reflecting heart rate, HRV, and basal stress levels. At the same time, in order to validate our TOI methodology, we compared the measurements obtained from TOI with those collected concurrently from an ECG system. We hypothesized that if there is a high positive correlation between data obtained from TOI and ECG, then cardiovascular changes as assessed by TOI should correspond with those by ECG, which were previously proven to correlate with individual stress. Thus, we would provide evidence to suggest TOI to be a valid methodology for assessing stress conveniently, contactlessly, and remotely.

Chapter 2

2 Method

2.1 Participants

One hundred thirty-six healthy adults above 18 years of age (57 males; Mean Age = 24.33 SD: 8.62) participated in the study. The present study was conducted in accordance with the NIH research ethics guidelines, and was approved by Research Ethics Review Committee at the University of Toronto before contacting participants regarding the study (Appendix A & B). Participants were recruited through flyers (Appendix C) posted at the University of Toronto, Ryerson University, and George Brown College. Further participants from our database, who had previously taken part in our research and indicated interest in being contacted for future research were contacted through email (Appendix D). Participants were given full disclosure of the research protocol (Appendix E) at initial contact for the study and again before being presented with a consent form on the day of their scheduled participation. All participants signed a written informed consent form (Appendix F) prior to the experiment.

2.2 Materials

A 2-minute video of animated clouds moving through the sky was presented to participants on a computer screen, using E-prime 2.0. The computer screen was placed on a table in the centre of the study room.

The FDA approved BIOPAC physiological measurement system, BIOPAC MP150 (BIOPAC Systems, Inc., Goleta, CA, USA) was used to collect ECG data. Specifically, the electrocardiogram amplifier module (ECG100C) was connected to the BIOPAC system to record ECG signals. A three-lead configuration was used for collecting ECG data. The White lead was connected to SHIELD and VIN- on the ECG100C module. The Red lead was connected to SHIELD and VIN+. Finally, the Black lead was connected to GND. Alcohol swabs were used to clean participants' skin prior to the attachment of electrodes. Disposable electrodes were placed on participants' skin to obtain ECG data. ECG signals were displayed on a laptop, using AcqKnowledge v. 4.1(BIOPAC Systems, Inc., Goleta, CA, USA).

A novel transdermal optical imaging system was constructed to obtain the transdermal image sequences as participants viewed the cloud film. A digital video camera (Canon VIXIA HF R62) was positioned on a tripod approximately 20-30 cm away from the back of the computer screen, angled to record the participants' face at 60 frames/seconds. LED lights were positioned on both sides of the camera, uniformly illuminating the participant's face (see Figure 2). The imaging system was color-calibrated to ensure successful repetitive performance with reliable and accurate color measurements.

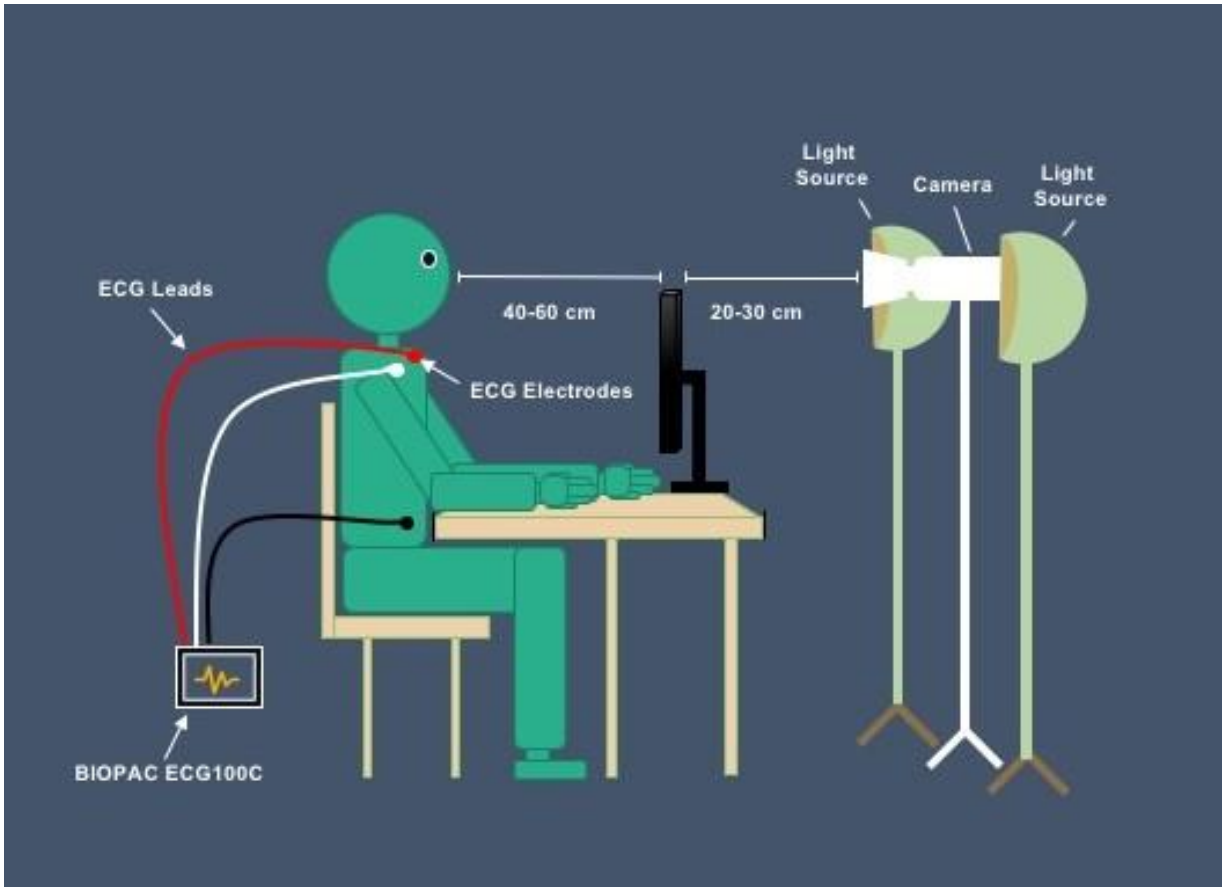


Figure 2. Set up of study.

2.3 Procedure

Participants were tested individually, seated in front of the computer screen in a quiet room, under supervision from an experimenter. Participants were asked to sit naturally, and at a comfortable distance (about 40-60 cm) from the computer screen while the experimenter sat behind the participant, at the corner of the room, out of the camera and participants' view. Next,

participants were told that they would be presented with a relaxing film of clouds moving through the sky and they must keep their eyes on the computer screen while maintaining a neutral facial expression throughout the duration of the film.

Before the cloud film was presented to participants, the experimenter instructed participants to place ECG electrodes based on Einthoven's triangle; near the right shoulder, left shoulder, and right hip. The White lead was attached to the electrode placed on participants' right shoulder. The Red lead was attached to the electrode placed on participants' left shoulder. Finally, the Black lead was attached to the electrode placed on participants' right hip (see Figure 3).

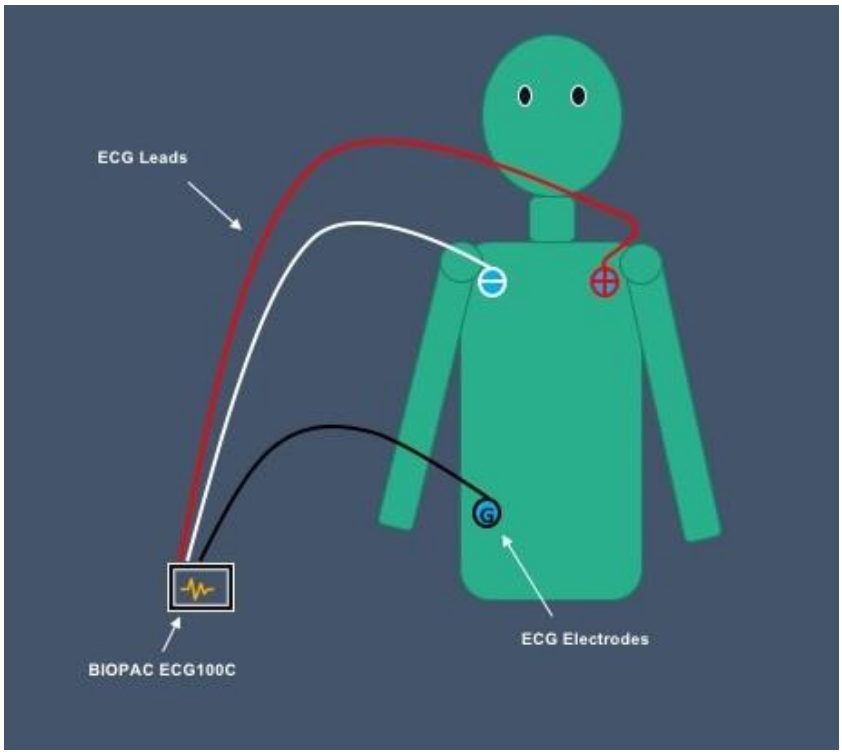


Figure 3. Placement of ECG electrodes on participants' body.

Once a clear ECG signal was presented on the laptop with AcqKnowledge, the experimenter adjusted the digital video camera to capture participants' face and began recording. With both TOI and BIOPAC, collecting physiological data from participants, the experimenter presented the cloud film to participants for 2 minutes.

2.4 Data Analysis

2.4.1 BIOPAC ECG Analysis

Each participant's raw ECG data was processed using MATLAB (The MathWorks, Inc). First, we estimated the R-wave peaks and the difference in time interval between the peaks to generate the RRI and in effect the HRV. Next, we used Poincaré plot (Kamen, Krum, & Tonkin, 1996) to analyze various features of HRV, specifically SD1/SD2, as research has shown this feature to be indicative of stress (Melillo, Bracale, & Pecchia, 2011). We plotted each individual's RRI against the next RRI on a graph with RR(n) on the x-axis vs. RR(n+1) on the y-axis.

In order to analyze SD1/SD2, we first determined SD1, which is defined as the dispersion (standard deviation) between points in the direction perpendicular to the line of identity on the Poincaré plot. SD1 reflects the short-term variation of heart rate caused by RSA, and thus are thought to indicate the activation of the parasympathetic nervous system. SD1 measurements were obtained using the following formula:

$$\mathrm{SD1} = \frac{\sqrt{2}}{2}\,\mathrm{SD}(\mathrm{RR_n} - \mathrm{RR_{n+1}})$$

Next, we determined SD2, which is defined as the dispersion (standard deviation) between points along the line of identity on the Poincaré plot. SD2 reflects the long-term variation of heart rate caused by RSA, and thus are thought to indicate the activities of the sympathetic and parasympathetic nervous system. SD2 measurements were obtained using the following formula:

$$\mathrm{SD2} = \sqrt{2\mathrm{SD}(\mathrm{RR_n})^2 - \frac{1}{2}\,\mathrm{SD}(\mathrm{RR_n} - \mathrm{RR_{n-1}})^2}$$

Finally, we determined SD1/SD2, which is defined as the ratio of dynamic change in the heart rate variability time series. SD1/SD2 reflects the relationship between the sympathetic and parasympathetic nervous system, which can be used as an indicator of individual stress level, with the lower ratios to indicate higher levels of stress.

2.4.2 Transdermal Optical Imaging Analysis

Transdermal optical imaging (TOI) analysis is a novel imaging method that is capable of isolating hemoglobin concentration (HC) from raw human face images taken from a conventional digital camera. This analysis is based on the fact that the human facial skin is translucent (Brunsting & Sheard, 1929; Dawson et al., 1980; Edwards & Duntley, 1939). Light travels beneath the skin, and re-emits after travelling through different skin tissues. The re-emitted light may then be captured by optical cameras (Anderson, 1991; Demirli et al., 2007; Stamatas et al., 2004). The dominant chromophores affecting the re-emitted light are hemoglobin and melanin (Nishidate et al., 2004). Since hemoglobin and melanin have different color signatures, it has been found that it is possible to obtain images mainly reflecting HC under the epidermis. Capitalizing on this, TOI analysis first obtains each captured image, and then performs operations upon the image to generate a corresponding optimized hemoglobin concentration (HC) image of a participant's face.

Isolating HC is accomplished by analyzing bitplanes in the video sequence to determine and isolate a set of the bitplanes that provide high signal-to-noise ratio (SNR) with regard to the facial cardiovascular activities. The determination of high SNR bitplanes is made with reference to a first training set of images constituting the captured video sequence coupled with facial blood flow measurements concurrently taken with FDA approved medical instruments that measure cardiovascular activities on the face (facial blood flows with a laser Doppler machine, and blood pressure waves with a continuous cuff-based oscillatory blood pressure monitor).

With respect to bitplanes, a digital image consists of a certain number of pixels; typically referred to as a configuration of width-times-height. Each pixel has one or more channels associated with it. Each channel has a dynamic range, typically 8 bits per pixel per channel. For color videos, each image typically has three channels: Red, Green, and Blue (RGB). As such, a bitplane is a view of a single bit of an image across all pixels (i.e., a 1-bit image per bit per channel).

Using the raw images that consist of all bitplanes of all three RGB channels, signals that change over a particular time period (e.g., 120 seconds) on each of the pixels are extracted. Using the signals from each pixel, machine learning is employed to systematically identify bitplanes that will significantly increase the signal differentiation and bitplanes that will contribute nothing or

decrease the signal differentiation. After discarding the latter, the remaining bitplane images optimally determine the blood flow. To further improve SNR, the result can be fed back to the machine learning process repeatedly until the SNR reaches an optimal asymptote. The machine learning process involves manipulating the bitplane vectors using image subtraction and addition to maximize the signal differences in all ROIs over the time period for a portion (e.g., 70%, 80%, 90%) of the subject data and validate on the remaining subject data. The addition or subtraction is performed in a pixel-wise manner. The resulting images thus contain information corresponding to hemoglobin concentration in each pixel, which were then put together as video images to reflect hemoglobin concentration changes in all parts of the face (for details, see Lee & Zheng, 2016).

For the present study, we divided the face into nine regions of interests (ROIs): Forehead Small, Nose Between Eyes, Nose Bridge Full, Nose Tip Small, Right Cheek Narrow, Left Cheek Narrow, Upper Lip, Lower Lip, Chin Small (Figure 4). We averaged the data obtained from all pixels in each ROI to further increase SNR. Next, we applied Hilbert-Huang transform to filtered ROI signal (Li, Kwong, Yang, Huang, & Xiao, 2011). The transform provided us with the principle frequency component of TOI signal. Using synthesized frequency, peaks of heartbeat were reconstructed to obtain heart rate and the intervals between heartbeats (i.e., RRI) were measured.

Using the above process, each video of participant's face was analyzed for facial blood flow information that reflects cardiovascular activities that correlate with stress. With a reconstruction of the peaks of heartbeat and a measurement for RRIs, we obtained stress in the same way that we extracted the information from data collected using the BIOPAC ECG. We plotted the RRIs on a Poincaré plot and analyzed for HRV features, specifically SD1/SD2.

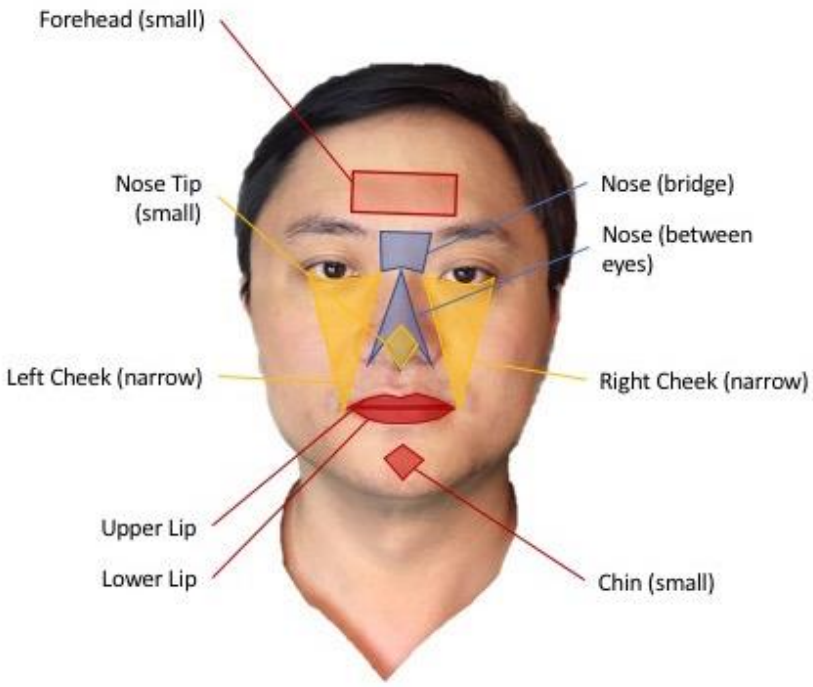


Figure 4. Nine regions of interests (ROIs) illustrated on the face of Dr. Paul Zheng, a contributor to the data analysis of this thesis. All participants, whose image have been used for this thesis, signed a written informed consent for release of their images in published articles (Appendix G) prior to inclusion of their image in this thesis.

2.4.3 Statistical Analysis

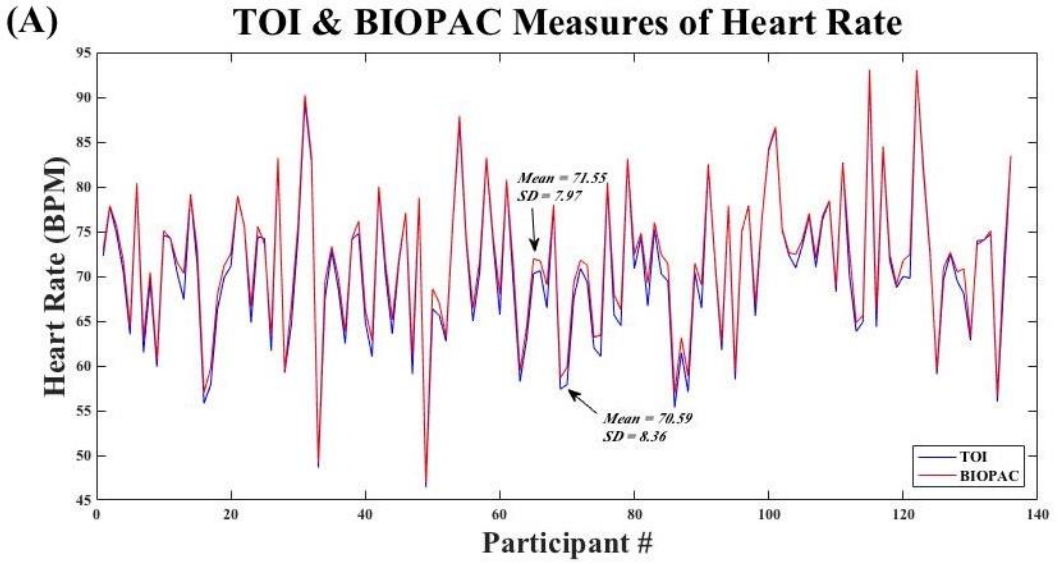
To compare the data collected from TOI against those from the BIOPAC ECG, we used MATLAB to assess the agreement and correlation between TOI and BIOPAC measurements, specifically for measures of heart rate and SD1/SD2 (i.e., stress). We assessed agreement by constructing Bland-Altman plots for the measures of heart rate and stress obtained from TOI and BIOPAC. The Bland-Altman plot is often used to determine the differences between two measurements, with the mean difference signifying bias and the standard deviation of the differences signifying the limits of agreement. We computed 95% limits of agreement for comparison of TOI and BIOPAC measurements. We assessed correlation by calculating for the correlation coefficients between measures of heart rate and stress obtained from TOI and BIOPAC.

Chapter 3

3 Results

3.1 Mean Heart Rate and Stress

To assess the accuracy of the transdermal optical imaging (TOI) technology, we compared measurements of heart rate and stress obtained with TOI against those obtained with the BIOPAC ECG. Figure 5A shows that the average (SD) of heart rate as obtained from TOI was 70.59 (8.36) beats per minute (BPM), while that obtained from BIOPAC was 71.55 (7.97) BPM. Figure 5B shows that the average (SD) of SD1/SD2 (i.e., stress) as obtained from TOI was .11 (.03), while that obtained from BIOPAC was .11 (.03).



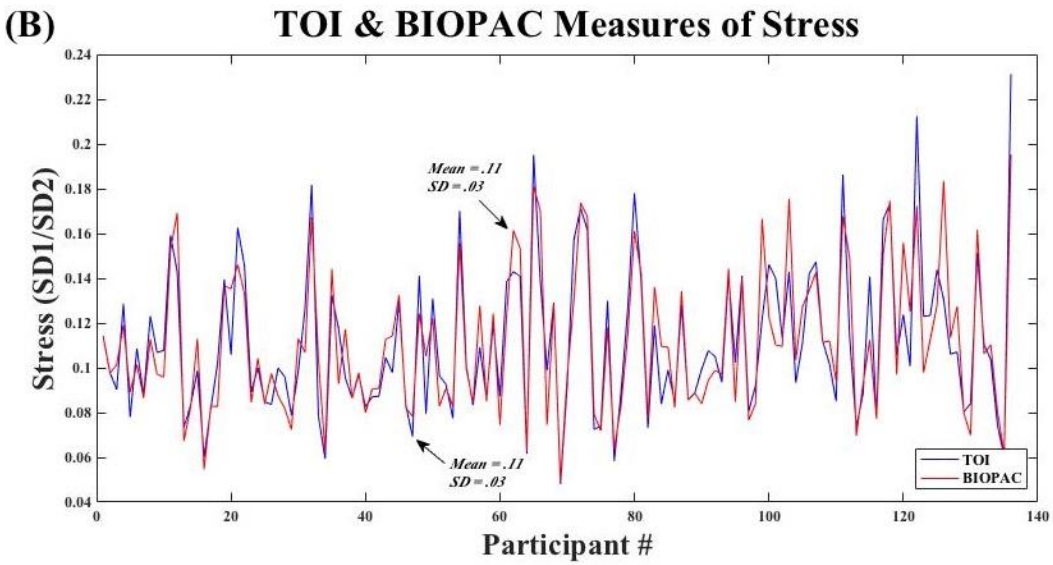


Figure 5. (A) Mean and standard deviation of participants' heart rate obtained from TOI and BIOPAC. (B) Mean and standard deviation of participants' stress from TOI and BIOPAC.

3.2 Agreement between TOI and BIOPAC ECG

We calculated for the agreement between heart rate measurements obtained from TOI and BIOPAC. We found that the agreement limits are from -2.55 to .63, with a bias of -.96 (see Figure 6A). Next, we calculated for the agreement between stress measurements obtained from TOI and BIOPAC. We found that the agreement limits are from -0.03 to 0.03, with a bias of 0 (see Figure 6B).

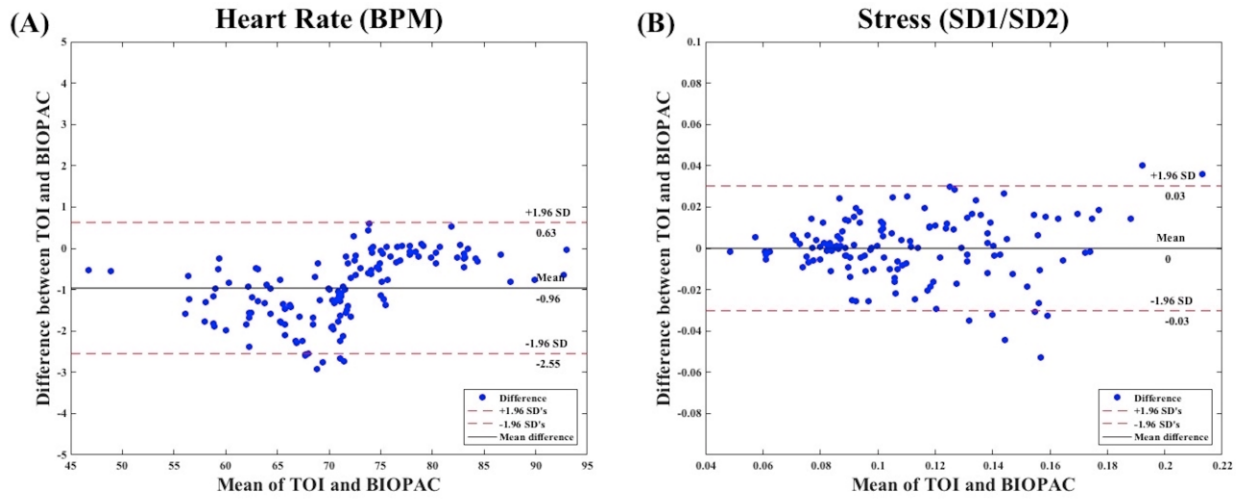


Figure 6. (A) Bland-Altman Plot comparing measures of heart rate obtained from TOI and BIOPAC. (B) Bland-Altman Plot comparing measures of stress obtained from TOI and BIOPAC.

3.3 Correlation between TOI and BIOPAC ECG

We calculated for the correlation between heart rate measurements obtained from TOI and BIOPAC. We found that there was a positive correlation between the two instruments, $r = 1.00$. Figure 7A demonstrates the points of heart rate (BPM) as obtained from TOI and BIOPAC with a line of best fit drawn through the points to illustrate the positive correlation. This extremely strong, positive correlation between measurements of heart rate obtained from TOI and those obtained from the BIOPAC ECG indicated that TOI technology is able to measure heart rate as accurately as the BIOPAC ECG.

We calculated for the correlation between stress measurements obtained from TOI and BIOPAC. We found that there was a positive correlation between the measurements of stress obtained from TOI and BIOPAC, $r = .89$. Figure 7B demonstrates the points of stress (SD1/SD2) as obtained from TOI and BIOPAC with a line of best fit drawn through the points to illustrate the positive correlation. This strong, positive correlation between measurements of stress obtained from TOI and BIOPAC indicated that TOI technology is able to determine stress as accurately as the BIOPAC.

In summary, we found that there were strong, positive correlations between physiological measurements obtained from TOI and those obtained from the BIOPAC ECG. Thus, results revealed TOI to be a contactless instrument that can determine changes in human physiology, specifically heart rate and stress level, with the same amount of accuracy as existing medical instruments used for heart rate and stress assessment.

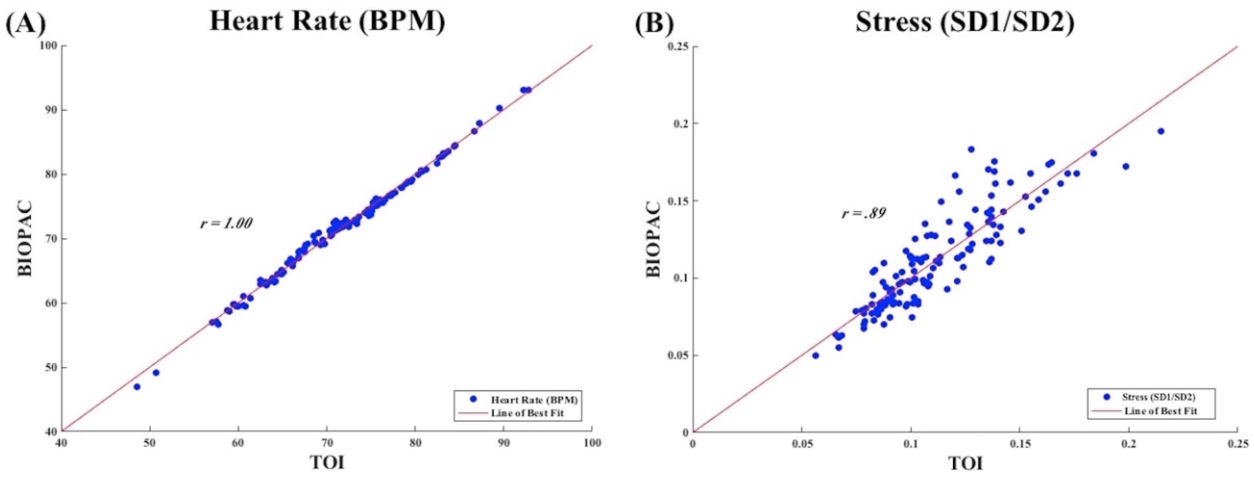


Figure 7. (A) Measures of heart rate from TOI and BIOPAC. (B) Measure of stress from TOI and BIOPAC.

Chapter 4

4 Discussion

4.1 Summary of Findings

The present study revealed strong positive correlations between measurements of heart rate and stress as obtained from the novel transdermal optical imaging technology (TOI) and from FDA

approved BIOPAC physiological measurement system, specifically the ECG100C. We found that by applying the TOI methodology, we can use a conventional digital camera on the face to accurately determine cardiovascular changes and psychological stress conveniently, contactlessly, and remotely.

The ECG is currently the most effective instrument to be used at determining cardiovascular activities and in particular, HRV with regard to measuring individual stress. In particular, extensive amounts of research have been utilizing HRV features computed from ECGs to indirectly derive stress levels (Sharpley & Gordon, 1999; Tavel, 2001). However, the utilization of ECG and other instruments for extraction of HRV (e.g., photoplethysmography; Giardino, Lehrer, & Edelberg, 2002) can be inconvenient given the need to attach electrodes or sensors onto the body. In contrast, TOI conveniently utilizes a regular digital camera and machine learning algorithms to extract HRV and infer stress levels contactlessly and remotely. Our findings of high positive correlation between measurements obtained from TOI and BIOPAC ECG testifies to the validity of TOI in determining heart rate and HRV to derive stress.

4.2 Limitations

Of course, while the present study's results highlight the potential value of using TOI to measure heart rate, HRV, and to derive stress, several limitations should be acknowledged. First, the study involved a small sample of one hundred thirty-six adults. With such a small sample it is difficult to determine whether the strong correlation between measurements obtained from TOI and BIOPAC can be generalized to a broader population. There is a need to assess the validity of TOI against the ECG on more people. Second, the study only compared data obtained from TOI against those from ECG, but there are other methods of stress assessment such as questionnaires for self-reports of stress and photoplethysmography (PPG; Giardino et al., 2002) that has also been proven to be reliable in extracting HRV features which reflect stress. There is a need to compare data obtained from TOI with those from other reliable stress assessment methods to further validate TOI.

Third, we only analyzed non-linear features of HRV, specifically SD1/SD2, which is indicative of stress (Mellilo et al., 2011), but time and frequency domain features have also been shown to reliably correlate with stress. Time domain features of HRV such as the standard deviation of an RRI (SDRR), the square root of mean squared difference of successive R-Rs (RMSSD), and the

proportion of NN50 divided by total number of normal-to-normal (NN) interval that differ more than 50ms (pNN50) have been shown to decrease under stress. In addition, frequency domain features of HRV such as high frequency power (HF), and low frequency to high frequency power ratio (LF/HF) have been shown to reliably correspond with stress such that the former decrease with stress while the latter increase with stress (Castaldo et al., 2015; Giardino et al., 2002; Shaffer, McCraty, & Zerr, 2014). Thus, there is a need to conduct further analysis of HRV features obtained via TOI.

Fourth, the study only assessed participants' stress during a 2-minute resting period, which is relatively short (Smith, Owen, & Reynolds, 2013; Munoz et al., 2015). Preferably, the recording duration should be longer, for example, for 5 to 6 minutes (Tharion, Parthasarathy, & Neelakantan, 2009; Castaldo et al., 2015). Future studies need to compare whether the short and long recording durations would produce consistent measurements. Furthermore, the present study used a relaxing video and therefore only provided us with information regarding participants' basal stress level. Further research is needed to include both resting and stressful periods to investigate whether TOI can accurately pick up acute stress caused by a stressful event.

4.3 Future Directions

Despite these limitations, the results of the present study still provide a strong proof of concept for the utility of TOI in measuring heart rate, HRV, and deriving stress measures. Given the convenient, contactless, and remotely operable features of TOI, future research would benefit in utilizing TOI to examine various aspects of stress. First, TOI can be placed anywhere in a research facility and used by anyone to collect data regarding a participant's stress (Figure 8). This would highly benefit any study assessing stress because it would only require a small room and the click of the recording button of the webcam to determine an individual's stress.

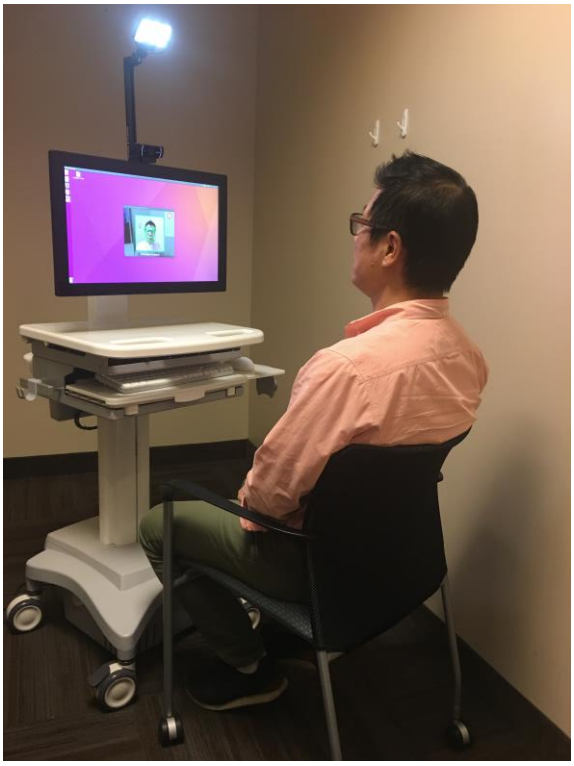


Figure 8. Set up of TOI station with Dr. Kang Lee, sitting as a participant. All participants, whose image have been used for this thesis, signed a written informed consent for release of their images in published articles (Appendix G) prior to inclusion of their image in this thesis.

Second, even without a TOI station, the TOI methodology can be applied to videos captured by remotely controlled cameras. Of course such utilization of the TOI methodology can present ethical issues, potentially infringing upon personal rights to privacy. Thus, there is a need to ensure that all applications of TOI methodology to captured videos are made aware to the subject(s) of videos and consent is obtained before utilization of TOI, as was the case for the present study. With consent for video recording and application of TOI, this setup would allow for naturalistic observation of participants during stressful events as the use of a camera can be done contactlessly and remotely. This would highly benefit studies attempting to assess participants' stress in their natural environments, during highly stressful periods (e.g., when university students are taking an exam in the examination halls) as compared to low stress periods (e.g., when the same students return from a vacation) (Melillo et al., 2011; Castaldo et al., 2016).

Third, with digital video cameras installed in mobile devices such as laptops, tablets, and mobile phones, we can use TOI at a multitude of locations (e.g., medical facilities, business offices,

homes) to assess people's stress for a long duration of time without causing discomfort. This would help medical facilities ensure the cardiovascular and psychological health of patients. It would also help organizations to ensure the efficient work of employees without endangering their health. This is particularly the case for occupations that often involve highly stressful situations (e.g., police officers, teachers, stockbrokers). Finally, TOI would help individuals to ensure their own wellbeing. With Apps installed in personal mobile devices such as mobile phones, we can use the existing cameras to capture video images of our face and the blood flow underneath to reflect our physiological and psychological states. This would allow people to monitor their stress anywhere they go, helping them ensure that their stress stays within a healthy range. Given that stress can lead to cardiovascular diseases, cognitive dysfunctions, and psychological disorders, the application of the TOI technology for monitoring stress would have a wide range of economic, societal, and personal benefits.

4.4 Conclusion

The present study examined the accuracy of the transdermal optical imaging (TOI) technology in comparison to the FDA approved BIOPAC system ECG100C for measuring heart rate and HRV, which reflects stress. We found that measurements of heart rate and SD1/SD2 (i.e., stress) obtained from the TOI technology highly corresponded with those obtained from the BIOPAC. Taken together, the findings of this study suggest that TOI can determine heart rate, HRV, and infer stress of an individual with high accuracy. Thus, the present findings reveal that the novel transdermal optical imaging technology can be used as a new methodology to study physiological and psychological changes in humans contactlessly, inexpensively, and conveniently.

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Appendix A

Ethics Approval Letter for the Initial Protocol

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

PROTOCOL REFERENCE # 32755

March 24, 2016

Dr. Kang Lee
DEPT OF APPL. PSYCHOLOGY & HUMAN DEVEL.
OISE/UT

Dear Dr. Lee,

Re: Your research protocol entitled, "Deception detection"

ETHICS APPROVAL	**Original Approval Date: March 24, 2016** **Expiry Date: March 23, 2017** **Continuing Review Level: 1**

We are writing to advise you that the Social Sciences, Humanities, and Education Research Ethics Board (REB) has granted approval to the above-named research protocol under the REB's delegated review process. Your protocol has been approved for a period of **one year** and ongoing research under this protocol must be renewed prior to the expiry date.

Any changes to the approved protocol or consent materials must be reviewed and approved through the amendment process prior to its implementation. Any adverse or unanticipated events in the research should be reported to the Office of Research Ethics as soon as possible.

Please ensure that you submit an Annual Renewal Form or a Study Completion Report 15 to 30 days prior to the expiry date of your current ethics approval. Note that annual renewals for studies cannot be accepted more than 30 days prior to the date of expiry.

If your research is funded by a third party, please contact the assigned Research Funding Officer in Research Services to ensure that your funds are released.

Best wishes for the successful completion of your research.

Yours sincerely,

Matthew Brower, Ph.D.
REB Chair

Research Oversight and Compliance Office - Human Research Ethics Program
McMurrich Building, 12 Queen's Park Crescent West, 2nd Floor, Toronto, ON M5S 1S8 Canada
Tel: +1 416 946-3273 ● Fax: +1 416 946-5763 ● ethics.review@utoronto.ca ● http://www.research.utoronto.ca/for-researchers-administrators/ethics/

Appendix B

Ethics Amendment Approval Letter for Protocol in Present Study

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

PROTOCOL REFERENCE # 32755

July 21, 2017

Dr. Kang Lee
DEPT OF APPL. PSYCHOLOGY & HUMAN DEVEL.
OISE/UT

Dear Dr. Lee,

Re: Your research protocol entitled, "Transdermal imaging study"

We are writing to advise you that a member of the Social Sciences, Humanities, and Education Research Ethics Board (REB) has granted approval to an amendment (Received June 13, 2017) to the above-referenced research protocol under the REB's delegated review process. This amendment approval letter only applies to what was outlined in the request form under section 5.a) or otherwise marked in the revised protocol.

Any changes to the approved protocol or consent materials must be reviewed and approved through the amendment process prior to its implementation. Any adverse or unanticipated events should be reported to the Office of Research Ethics as soon as possible.

Best wishes for the successful completion of your research.

Yours sincerely,

Matthew Brower, Ph.D.
REB Chair

Research Oversight and Compliance Office - Human Research Ethics Program
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Appendix C

Recruitment Flyer

PARTICIPATE IN RESEARCH!
GET $10 IN COMPENSATION!

The University of Toronto Development Lab is currently looking for students to participate in a study examining transdermal imaging of facial blood flow information.

Who: Adults above 18 years of age

What: You will be seated in front of a computer to view a video with tranquil music. You will have some non-invasive devices attached to you to measure your heart rate, respiration, skin conductance, blood pressure, blood flow, and oxygen saturation. You will also have your blood pressure measured by experimenters!

Where: Ontario Institute for Studies in Education – 252 Bloor St. W.

When: Anytime that is convenient to you! The study only takes 15-30 minutes!

How: To book an appointment or for more details call 416-934-4503 or email detectionstudies@gmail.com

Appendix D

Email Recruitment

Dear (participant name),

Greetings from the Development Lab at the University of Toronto. You have previously indicated interest in being part of our research studies so I am emailing you today to let you know that we currently have a new study going that you are eligible to participate in, so I have included a short summary of it below in case you are interested. However, if you have any questions or concerns, please fell free to contact me at 416-934-4503.

For this study, you will be asked to fill out an information sheet regarding your medical history. You will also have your height, weight, body fat, arm length, arm circumference, waist size, and facial dimensions measured with a scale and measuring tape. Then you will be seated in front o f a computer to view a video with tranquil music. We would like you to focus on the video presented to you and try not to move too much during the study. The purpose of this task is to see if we can use facial blood flow information to determine your physiological changes. During the study, you will be video recorded. In addition, we will be measuring your heart rate, respiration, skin conductance, blood pressure, blood flow, and oxygen saturation using some non-invasive devices and/or having experimenters determine your physiological condition, specifically blood pressure.

Since this study involves the use of electrodes, it is recommended that participants wear short sleeved shirts to allow for easy use of the equipment.

All information and video recordings during this study will remain confidential by removing links between data and your identity, unless required for legal reason. All collected data will be combined with those of other participants, and only group results will be reported.

The entire study will take approximately 15-30 minutes, however we ask that you schedule 1 hour out of your day if you decide to participate as we do not wish for you to be rushing to your next appointment should anything run late. In addition, to thank you for your time, you will receive $10 compensation.

Most people find this to be an extremely interesting experience, and we hope that you will get a chance to experience it for yourself as well. If you are interested in participating, please reply to this email, or call us at 416-934-4503. We will be happy to schedule an appointment for you.

Thank you very much and we hope to hear from you soon!

[Research Assistant name]
Research Assistant
Dr. Kang Lee’s Development Lab
University of Toronto

Appendix E

Information Sheet

ONTARIO INSTITUTE FOR
STUDIES IN EDUCATION
OF THE UNIVERSITY OF TORONTO
252 Bloor Street West
Toronto, Ontario, Canada, M5S 1V6
Telephone: (416) 923-6641

Dear participant,

We would like to invite you to participate in a transdermal imaging study that is being conducted by Dr. Kang Lee's Development Lab at the University of Toronto. In this study, we will be examining the use of facial blood flow information for measuring your health condition. The study will involve one session which will take approximately 15-30 minutes of your time and is located at the University of Toronto. Please read the following information provided to get a fuller understanding about the tasks and what your role would be in our research.

For this study, you will be asked to fill out an information sheet regarding your medical history. You will also have your height, weight, body fat, arm length, arm circumference, waist size and facial dimensions measured with a scale and measuring tape. Then you will be seated in front of a computer to view a video with tranquil music. We would like you to focus on the video presented to you and try not to move too much during the study. The purpose of this task is to see if we can use facial blood flow information to determine your physiological changes. During the study, you will be video recorded. In addition, we will be measuring your heart rate, respiration, skin conductance, skin perfusion, blood pressure, blood flow, and oxygen saturation using some non-invasive devices and/or having experimenters determine your physiological condition, specifically blood pressure.

Please also be advised that your face will be illuminated with a photography light during the study. This may increase the likelihood of a seizure in people with photosensitive epilepsy.

Over the course of this experiment, signs of cardiovascular abnormalities may become apparent in electrocardiogram (ECG) traces or otherwise. Several of our research personnel are also trained nurses, and thus are capable of identifying these abnormalities. In the event that we identify an abnormality with potentially significant clinical consequences, we may disclose this fact to you and recommend that you follow up with your physician to confirm the finding. Such a disclosure may cause you some distress but could ultimately benefit you by informing you about a significant risk to your health. You can indicate your preference to decline such a disclosure on the written consent form. Please note that this study should not be considered a clinical examination, and you should not rely upon our observations to ascertain your health status.

For helping us with the study, you will be rewarded $10. There may be minor physical risks due to discomfort in applying and removing the non-invasive electrodes. There are no known personal benefits. Your participation in this study is completely voluntary and you may choose to

decline participation, withdraw at any point in the study, and refuse to answer any questions or complete any part of the procedure – all without any consequences. If you have any questions about your rights as a participant, you may contact the Office of Research Ethics at ethics.review@utoronto.ca or 416-946-3273.

All information and video recordings during this study will remain confidential by removing links between data and your identity, unless required for legal reasons. All collected data will be combined with those of other participants, and only group results will be reported. To thank you for your time, you will receive $10 compensation regardless of withdrawal.

The research study you are participating in may be reviewed for quality assurance to make sure that the required laws and guidelines are followed. If chose, (a) representative(s) of the Human Research Ethics Program (HREP) may access study-related data and/or consent materials as part of the review. All information accessed by the HREP will be upheld to the same level of confidentiality that has been stated by the research team.

Thank you for your interest in our research. If you have any questions, concerns, or would like to participate in this study, please contact us at detectionstudies@gmail.com.

Sincerely,

Dr. Kang Lee
Professor & Tier 1 Canada Research Chair
OISE/University of Toronto
Phone: 416-934-4597
E-mail: kang.lee@utoronto.ca

Appendix F

Consent Form

Having read the enclosed materials, I _____:

□ Consent to participate in this study □ Do not consent to participating in this study

□ Please do NOT inform me in the event that signs of a health abnormality are detected during this study.

Date of Birth (mm/dd/yy) _____

Signature _____ Date _____

Mailing
Address:_____

_____

E-mail Address: _____

Phone:_____

Please provide contact information if you would like a summary of the results
□ Same as above

Mailing
Address:_____

_____

E-mail Address: _____

Phone:_____

Prefer results by: □ Mail □ E-mail

Would you be willing to have us contact you at a later time for related research?
_____ YES _____ NO

Appendix G

Photo Release Consent Form

Release Form for Use of Photograph/Video Recording

Transdermal Facial Blood Flow Patterns Reliably Reveal Stress Levels
Release Form for Use of Photograph/Video Recording

Kang Lee, Ph.D.
Professor & Tier 1 Canada Research Chair
Dr. Eric Jackman Institute of Child Study
University of Toronto
kang.lee@utoronto.ca

Please print:

Name of Participant: _____

Address: _____

I hereby give my permission to Dr. Kang Lee to use any photos or video recording material taken of myself during his research on "Transdermal Facial Blood Flow Patterns Reliably Reveal Stress Levels". The photos and videotape material will only be used for research purposes and for the presentation of the research in published articles and/or conference presentations. I understand that Dr. Kang Lee has permission to edit video footage or select photos as he sees fit. I understand that my, name, likeness and other identifying information will be incorporated as part of the research. As with all research consent, I may at any time withdraw permission for photos or video footage of me to be used in this research project. If I do not withdraw my permission, I understand that my permission is given in perpetuity (without a concluding date). I understand that I will not be compensated for the use of my likeness unless agreed upon as part of the larger research project.

Signature: _____ Date: _____