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Integration of multiple physiological signals to evaluate the human body's response to an environmental challenge

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Abstract— **This paper details the combination of heart rate, core body temperature, and actigraphy in an ambient daily living environment to enhance the understanding of the overall physiology of the human body. Such research represents a new advancement in the area of physiological measurements. Measurement of a single physiological variant only provides one aspect of the body's response to the environment while the combination of multiple measurements can clarify the complex physiological response. The combination of physiological measurements in filed exercises has demonstrated that multiple physiological signals may better predict an individual's response to the environment. The integration of heart rate, core body temperature and actigraphy measurements are discussed. Applications exist in personal health, sports performance, and in hazardous material applications.**

Index Terms—**Heart rate; Core Body Temperature; Actigraphy**

I. INTRODUCTION

THE individual physiological parameters of heart rate, core body temperature, and actigraphy have been used for decades to assess physiological performance. The integration of these parameters provides a novel and effective way to assess physiological function in the ambient environment. Heart rate (HR) is a well-known and an easily-measured physiological parameter. Up until recently Core Body Temperature (CBT) was difficult to measure in a comfortable and accurate manner. And although there have been many models of accelerometers designed for the measurement of activity of daily living and sleep, validation and verification of these devices has not been well documented. In this paper the control of HR, CBT, and activity response during environmental challenge is examined.

Measurement of heart rate during exercise is extremely important to the understanding of energy expenditure, physical training, and the body's response to environmental challenge of the cardiovascular system. Accurate measurements of heart rate have been encumbered by the size of the monitor, difficulty of use, and the reliability of the measurement devices in the presence of movement artifacts. There is interest in developing accurate, small, non-intrusive monitors for use in exercise regimens where direct wire leads cannot be tolerated, where ease of use is critical, and where movements may give rise to artifacts.

In humans, the temperature of blood in the pulmonary artery (PA) is considered "true" core body temperature [1]. Rectal temperature has been found to track esophageal and pulmonary artery temperature quite closely (mean difference -0.4 ±1.0°C) [2]. A rectal probe connected to a body-worn data logger is often used to measure the circadian rhythm of core temperature over extended periods [3], [4]. As early as 1968 a temperature sensitive "radio pill" was proposed as a suitable device for monitoring core temperature [5]. The VitalSense system was developed to provide a more reliable means for measuring core temperature in ambulatory subjects. In studies with human volunteers VitalSense system was worn together with a rectal thermistor specifically measured core body temperature during normal daily activity comparing the established rectal probe and the VitalSense telemetric monitor and an ingested core body temperature capsule (Figure 1).

Most actigraphy devices utilize a motion sensor known as an "accelerometer" to monitor the occurrence and degree of motion. The accelerometer, also known as a "bi-morph element", is a two-layer sensor that exhibits the property of piezo-electricity. The piezo-electric effect occurs in certain dielectric crystals. When these materials are strained by the slight deformation of bending, a tiny surface charge is generated that transiently varies in magnitude. The charge produces a voltage, and more voltage is produced with increasing amplitude and speed of motion. The signal is amplified and digitized by the on-board circuit. This information is stored in memory on board the device as Activity Counts. Accelerometers can be mounted on different limbs or on the body trunk to measure motion. Variation in the placement of the device makes commonality of data among Actiwatches inconsistent if not carefully considered. Each accelerometer must be carefully calibrated to assure that data between watches is consistent. Proper placement of the Actiwatch will remove most variability within a patient population wearing different devices. To obtain the most repeatable results, it is important to develop a standardized mounting and positioning protocol. The Actiwatch® was used in these studies and has been validated for sleep and activity of daily living [6, 7].

Even though, most of the time these measurements are reviewed and reported independently, there is evidence that integration of physiologic measurements can lead to better data for evaluation of the human response to specific

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physiological challenges. The paper is organized as follows. In Section II, we review a dynamic model of circadian rhythm and the integration of core body temperature, dermal temperature, and actigraphy to more closely model the body's response to circadian phase. Section III presents heart rate and actigraphy as related to exercise stress and Section IV describes the integration of heart rate and core body temperature in determining Physiological Stress Index (PSI). In this paper, we propose to review several physiological challenges that may benefit by integration of physiological data. One of the benefits of this approach is that the data may provide a simple robust method of viewing the data for better understanding of physiological response to our ever changing environment.

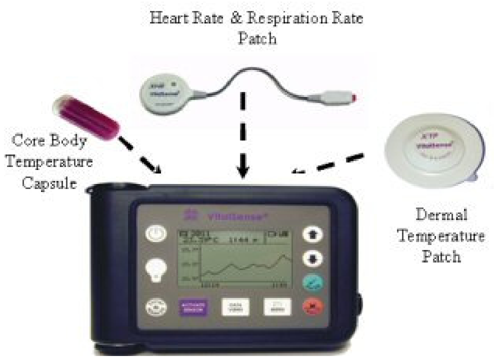

Fig. 1. VitalSense Physiological Vital Sign Monitor, Core Body Temperature Capsule, Heart Rate and Respiratory Rate Sensor, Dermal Temperature Patch.

II. Circadian Biology

This section gives a brief review of a circadian model using core body temperature, dermal temperature, and actigraphy. Monk et. al., measured the mean circadian temperature rhythm of a group of 28 subjects. The rhythm showed the usual classic shape, with a trough at ±01:00 h, a fairly steep rise through the morning hours, and a more gradual rise to mid-evening. The peak at 11:30 h reflected the time at which showers and exercise were permitted (thus temporarily increasing body temperature). The resulting group mean estimate for Tmin was 02:57 h. [4]. By adding actigraphy data to the temperature analysis of circadian phase we can more easily and accurately detect and align the body's circadian rhythm with sleep patterns (Figure 2). Integration of core body temperature and actigraphy help align the actual physiological response with a specific human activity.

III. Heart Rate and Stress

The combination of heart rate and activity can help to define the relationship between exercise induced tachycardia and stress related tachycardia. Work from the laboratory of Brent Ruby in Montana Wildland Firefighters provides data that support the concept that heart rate and activity can be used to link exercise induced increases in heart rate and stress related changes in heart rate [8]. Figure 3 shows a typical heart rate and activity trace from a wildland firefighter where on the first two days there is a typical relationship between activity and heart rate during the normal work day with a decreased activity and heart rate

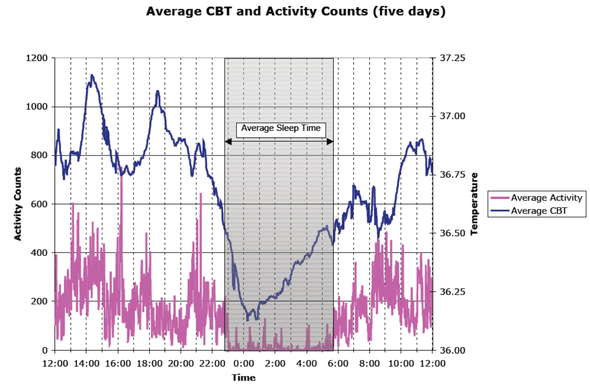

Fig. 2. Blue line is core body temperature as measured with the VitalSense Monitor and the Core Body Temperature Capsule. Pink line is the activity as measured by the Actiwatch. The grey section in the middle is the average sleep time.

during sleep. The third day show nicely that there is a work related increase in heart rate and then toward the end of the third day there is a significant increase in heart rate while activity drops to almost nothing. This is a period of stress where the fire is raging over the subject's fire blanket while he is in a stream bed. The use of two physiological variables was essential to the understanding of the physiological response to environmental and psychological stimuli.

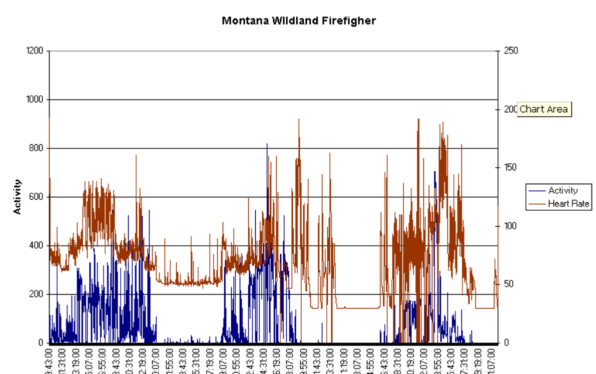

Fig. 3. Red line is heart rate as measured with the VitalSense Monitor and the XHR Heart Rate Sensor. The blue line is activity as measured by the Actiwatch**.**

IV. Heart Rate and Core Body Temperature

The Physiological Strain Index (PSI), first proposed by Moran (1998), is a computational integration of heart rate (HR) and body core temperature (Tc) and reflects the combined strain on the cardiovascular and thermoregulatory systems, respectively. The utility of the PSI has primarily been limited to lab-based research, but the PSI's true utility may be realized during actual environmental stress conditions where thermoregulatory challenges to the body are likely to limit physical performance. Figure 5, demonstrates how PSI is a mathematical calculation of the ratio between resting heart rate and core body temperature as related to current heart rate and core body temperature. The advantage of this equation is that it normalizes the individual's PSI with an environmental stress (Figure 5). The other advantage is that this measurement provides the health care professional with a simple scale from 0 to 10 and does not mandate that the evaluator interprets what is a normal core body temperature and heart rate and have these values changed out of a "normal range". The PSI has been used primarily in "heat stress" conditions, but also used to evaluate athletes in exercise bouts. The integration of two separate physiological variables that interact can be a better predictor of the response of the human body to an environmental challenge.

Physiological Strain Index

$$PSI = \frac{5(T_{coret} - T_{core0})}{(39.5 - T_{core0})} + \frac{5(HR_t - HR_0)}{(180 - HR_0)}$$

Fig. 4. Physiological Strain Index (PSI) where Tcoret is the current core temperature, Tcore0 is the initial core body temperature, HRt is the heart rate at the current time, HR0 I the initial heart rate. 39.5 oC is the definition of hyperthermia and 180 represents a moderate tachycardia. The number 5 is a correction factor.

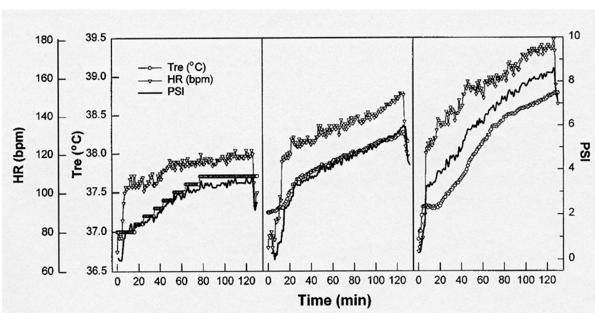

Fig. 5. Physiological Strain Index (PSI) (solid line), calculated from Tre (s) and HR (o) applied to 3 subjects exposed to the same heat stress (Moran, et. al.).

V. Concluding Remarks

This presentation reviews the integration of physiological data in an ambulatory setting to define the body's physiological response to environmental change. Based on three examples including; circadian rhythm, exercise and psychological stress, and physiological stress index to evaluate an individual's response to heat stress, we have reviewed the use of the VitalSense Physiological Monitor and the Actiwatch to integrate physiological parameters. The major benefit of this approach is that more than one physiological signal provide increased sensitivity and selectivity of the physiological response. And, in addition, by combining signals there may be the added benefit of removing individual variability from the measurement. Future development and application indicate that by integrating multiple sensors into a single monitor will improve the accuracy of evaluating the physiological state. In the future, we suggest that algorithms be developed to evaluate data through integration of multiple signals.

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