Continuous electronic data capture of cardiopulmonary physiology, motor behavior, and subjective experience with the LifeShirt: towards a comprehensive monitoring of affective states in real life

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ABSTRACT

Emotions powerfully influence our physiology, behavior, and experience. A comprehensive measurement of affective states in health and disease would register responses from each of these domains. In addition, since no single physiological parameter can index emotional states unambiguously, a broad assessment of physiological responses is desirable. We present a recently developed system, the LifeShirt™, which allows reliable ambulatory monitoring of a wide variety of cardiovascular, respiratory, motor-behavior, and experiential responses. The system consists of a comfortable garment with embedded inductive plethysmography sensors and a handheld computer for data recording and experience data input via touch screen. Parameters are extracted offline using sophisticated analysis and display software. The device is currently used in clinical studies, but is not limited to this application.

Keywords

Emotion, respiration, electrocardiogram, inductive plethysmography, affective computing, wearable computers

INTRODUCTION

Continuous ambulatory monitoring of the affective state of an individual can expand our understanding of emotions in daily life and their relationship to performance, health and disease. Emotional activation is manifest in three systems: the verbal-cognitive or language system, the behavioral-motor system, and the physiological system. The physiological system is multi-faceted, including a variety of cardiovascular, respiratory and electrodermal responses that are recruited differentially across a variety of behavioral contexts.

Respiration is an important physiological function that is multi-dimensional in nature. A detailed quantification of volume, timing and shape parameters in the respiratory pattern waveform can map well into different emotional states along the dimensions of affective valence and arousal (also called activation) [1, 6]. That is, individual responses either reflect the *quality* of the affective response on an axis that can be described as appetitive vs. defensive, like vs. dislike, pleasant vs. unpleasant, positive vs. negative connotation. An orthogonal axis defines the *intensity*, vigor, or urgency of that emotional quality.

Detailed measurement of respiratory responses has been neglected in emotion research and in clinical practice, in large part because of the difficulties obtaining accurate measurements, both in- and outside the laboratory. The scarcity of respiratory monitoring in clincial contexts is unsettling since any disturbance of respiratory function is potentially life threatening and carries great weight in clinical decisions. Long-term monitoring of respiratory function outside the hospital would be desirable for a variety of disorders that are known to be associated with respiratory abnormalities, e.g., chronic obstructive pulmonary disease, pulmonary emphysema, restrictive lung disease, asthma, cardiac failure, or epilepsy. Furthermore, since emotions can affect respiration profoundly, our understanding of a spectrum of mental and psychophysiological states and disorders associated with emotional activation would benefit from a detailed monitoring of respiratory function.

INDUCTIVE PLETHYSMOGRAPHY

Inductive plethysmography (IP) is the gold standard for unobtrusive respiratory monitoring and has been used widely in clinical and research settings. It was first implemented in the Respitrace™ device (Ambulatory Monitoring, Inc.) about 20 years ago [5]. Approximately 1,600 published scientific studies have used this technology and established it as the standard for non-invasive assessment of the pattern of breathing. This technique approximates the amount of air moved by the respiratory system by measuring the expansion and contraction of both the rib cage and abdominal compartments. An IP sensor consists of a sinusoidal arrangement of electrical wires embedded in elastic cotton bands. A high frequency, low voltage oscillating current is passed through the wires to generate a magnetic field needed to measure the self-inductance of the coils, which is proportional to the cross-sectional area surrounded by the band. Calibration of the rib cage and abdominal bands by a fixed volume bag and summing of the two signals allows measurement of tidal volume in ml.

In the past 5 years we have used in our research a portable multi-channel recording system (Vitaport 2) and the Respitrace device to study respiratory dysregulation in patients with anxiety disorders in their natural environment [7-9]. Significant limitations were the size, troublesome operation, and difficulty in holding the sensors in place during normal daily activities, which rendered the system inadequate for routine clinical use and large scale studies. In addition, in the absence of any satisfactory respiratory data analysis software we had to develop our own.

THE LIFESHIRT SYSTEM

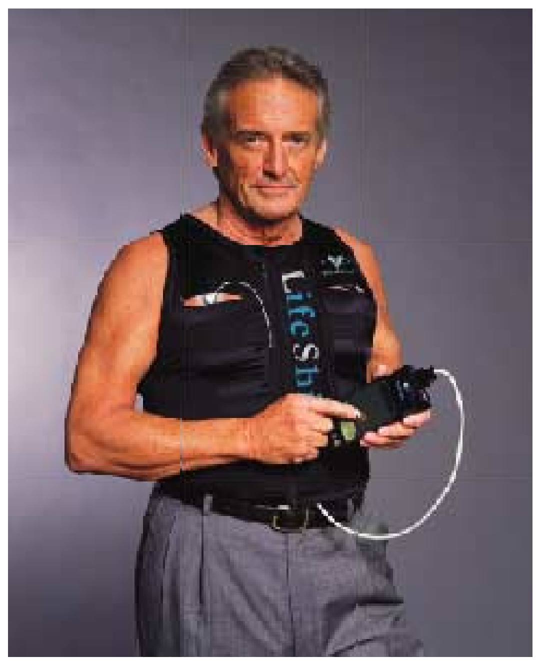
Much technical expertise and a substantial financial investment by VivoMetrics (www.vivometrics.com) has led to the development of the LifeShirt System™, which represents a great leap forward in ambulatory measurement technology. The LifeShirt is an easy to use non-invasive ambulatory monitoring system consisting of a comfortable garment with an array of embedded sensors, a commercially available handheld computer (Handspring Visor™) with data collection software, and a sophisticated software package (VivoLogic™) for comprehensive offline signal analysis, display, and report generation.

Cardiopulmonary Monitoring

A large number of cardiopulmonary parameters of clinical interest and emotion-relevance are extracted from the relatively small array of noninvasive sensors. The sensor array of the LifeShirt System is embedded in a sleeveless undergarment made of hand washable, reusable highly stretchable material that fits snugly and can be worn comfortably for extended periods. IP sensors for monitoring a variety of cardiopulmonary signals are embedded in the shirt. This ensures their correct and durable placement and makes it easier to set up the sensor array for multi-channel recording. The sensors, like their predecessors, the Respibands™, consist of a sinusoidal arrangement of electrical wires that are excited through an extremely low current, electrical oscillator circuit. The coils have a width of only about 1 inch, which is much less than the coils embedded in Respibands™. One sensor is sewn into the shirt at the level of the rib cage and one at the level of the abdomen. From these signals, the VivoLogic software extracts a variety of calibrated respiratory pattern measures such as minute ventilation (a proxy for oxygen consumption, which is directly related to total organismic metabolic activity), tidal volume, respiratory rate, fractional inspiratory ratio, and peak inspiratory flow. The software is so advanced that it can automatically detect and classify apneas or hypopneas (for example, into central, mixed or obstructive apneas), Cheyne-Stokes respiration, sighs, and coughs.

In addition to the two respiratory IP sensors, an important innovation, a single IP sensor is placed around the thorax to record chest wall movement resulting from heart activity ("thoracocardiography" or TCG). Under resting conditions, respiratory movement dominates the waveform with only approximately 3-5% of its content consisting of oscillations synchronous with the heartbeat. After suppression of respiratory movement with digital filtering and ECG triggered ensemble averaging, this signal reflects the stroke volume of the heart.

An electrocardiogram is recorded by means of three electrodes placed directly onto the skin on the upper chest and on the lateral surface of the abdomen. This standard configuration provides a single lead for heart rate and ECG waveform determinations. R-spikes in the ECG are detected, and the R-R intervals are converted to instantaneous heart rate. Respiratory sinus arrhythmia (RSA) is measured using the peak-to-trough method: for each breathing cycle, the shortest R-R interval during inspiration is subtracted from the longest R-R interval during expiration. RSA reflects parasympathetic neural control of the heart. Breath-by-breath RSA values can be normalized by tidal volume and respiratory rate, both important confounds in the estimation of changes in parasympathetic activity currently neglected in most research [2, 3]. The single-lead ECG waveform also allows a rough quantification of cardiac arrhythmias. However, since the P-wave can be invisible in a single lead, a 12-lead ECG is necessary for accurate classification of arrhythmias.



Actigraphy

For measurement of body posture (angle deviation from horizontal) a two-axis accelerometer is placed onto the shirt over the sternum. The rectified and integrated accelerometer signal is the highly sensitive motility signal used to quantifiy physical activity and identify periods of rest and sleep. This signal also permits focusing in on portions of the tracing in which motion artifacts might be present.

Other peripheral diagnostic devices with digital output may be used as components of the LifeShirt system for special purposes. These include pulse oximeter (for measurement of arterial oxygen saturation, pulse wave amplitude, and pulse transit time), ambulatory blood pressure recorder, or capnograph (for measurement of end-tidal pCO_2).

All sensors are attached via secure connectors and a cable tree to a small custom designed interface directly plugged into the port of a mass-produced handheld personal computer (Handspring Visor™). This compact and lightweight computer serves as a digital recorder and can be worn on a belt or put into the pocket of a jacket. The Visor captures raw waveforms from the LifeShirt with high sampling rates for full disclosure storage and off-line detailed analysis. An exchangeable flash memory card provides large storage capacity.

VivoLog Electronic Diary

An important module of the LifeShirt System software is the VivoLog™ which captures experience data from individuals. This data is input via the Visor touch screen and is recorded synchronized to the datastream of the physiological signals. Specific self-report items regarding mood state, symptoms, cognitions, and types of activities (e.g., "I feel anxious", "My heart is pounding", "I think I cannot achieve the task in time", and "I am typing"), instructions and reminders to perform certain tasks, and rating scales (Likert-type vs. visual analogue, specific anchors) can be preprogrammed for specific applications. Input contingency modes include "user triggered", "fixed timing", and "random timing."

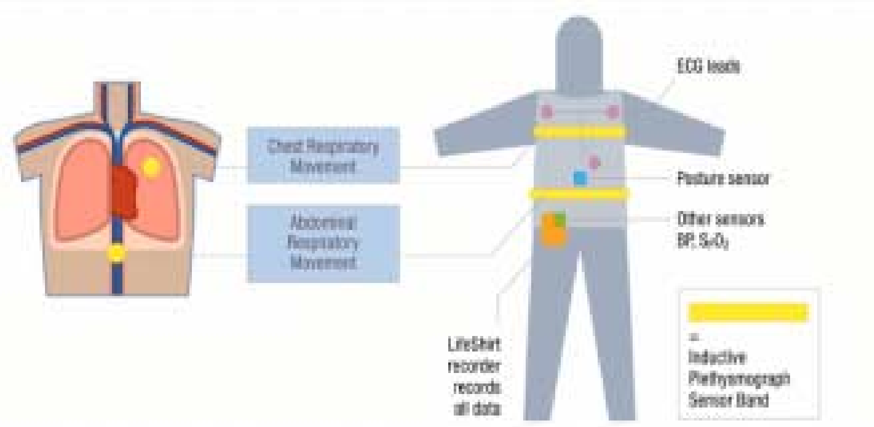
When the recording is finished, the data on the memory card can be transferred to a personal computer running under Windows. The VivoLogic software allows to review the quality of raw waveforms and extracted parameters, editing of artifactual segments that cannot be scored automatically, and marking of data segments of special interest. Visual inspection of all raw waveforms is not attempted since this would be unrealistic with the great amounts of data being processed. Instead, 1-min trends of derived parameters are presented as medians with their quartile ranges. Such analysis minimizes the influence of outliers that might spuriously affect mean values.

Sleep Monitoring

The LifeShirt System does not measure EEG, EOG, and EMG, which would be necessary measurements for standard sleep staging. However, breathing pattern analysis allows a rough discrimination among wake state, rapid eye movement (REM) sleep, and non-REM sleep in most individuals. For example, high values of tidal volume, respiratory rate, and heart rate along with motion artifacts on the breath waveform traces and high variability of end-expiratory lung volume are consistent with waking while lower values with sleeping, which usually allows distinguishing approximate sleep onset. Good markers of REM vs. NREM sleep are lower values of % rib cage volume/tidal volume (about 50% reduction from NREM) because of the accompanying partial thoracic respiratory paralysis and elevated levels of thoracoabdominal discoordination as expressed by high phase angles between rib cage and abdominal compartments. Together with the actigraph signal, sleep efficiency can be estimated.

CONCLUSIONS

The LifeShirt is a sophisticated system for measuring a variety of respiratory parameters related to emotional activation and disease. It is much improved compared to any previously available ambulatory respiratory monitoring systems in terms of ease of use and comfort. In addition, it has the capability of recording a variety of parameters related to cardiac function and can obtain posture and motility information important as control parameters for unsupervised monitoring. All the sensors and electronics are state-of-the-art technology and are integrated within a shirt and a small handheld computer device. The system is a logical extension of ECG Holter monitors and may open a new era in ambulatory monitoring for both scientific research and clinical practice.



Research on the emotion-respiration relationships has been largely restricted to respiration rate and tidal volume. Finer distinctions, such as peak inspiratory flow (a measure of breathlessness), or quantification of breathing suspension periods can add additional information to the assessment of the quality and intensity of emotional response. An unprecedented range of these and other respiratory parameters can be assessed with the LifeShirt technology. It can be used for ambulatory monitoring of physiologic parameters and motility during wake, sleep, and activity states. In addition, reports of mood, symptoms, and types of activity can be gathered automatically and reliably, overcoming the limitations of retrospective reports or paper and pencil diaries. In other words, all three emotional response systems - language, physiology, and motor behavior - are recorded. Intervals when patients reported specific symptoms can receive special attention in the inspection of physiological parameters.

The system is user-friendly enough to be used in clinical practice and in healthy individuals for obtaining information about their psychophysiological state, for example, during mental or sports performance or during human-computer interaction. One apparent area for application of this new technology is the monitoring of breathing patterns and cardiovascular responses over extended periods in individuals who experience anxiety and stress. Many unresolved issues leave our current understanding of emotions in daily life incomplete. The comprehensive cardiopulmonary, gross motor behavior, and subjective experience assessment achievable with the LifeShirt System should help advance this understanding.

FUTURE WORK

A next step can be the development of a real-time interface utilizing the affective information obtained with the LifeShirt for biofeedback training and for optimizing human-computer interaction. Future implementations of the VivoLog software will allow the input modes "activity/posture triggered" and "physiological abnormality triggered" to collect experience data under specified organismic conditions, e.g., during rest or during extended heart rate increases out of proportion to ongoing physical activity ("additional or emotional heart rate")[4, 10].

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