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A Novel Approach for Measuring Energy Expenditure in Free-Living Humans

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***Abstract*—Measuring energy expenditure (EE) in free-living humans is difficult. In this study, we validated a novel instrument that measures free-living EE from direct calorimetry, i.e. the heat produced by the body. The sensor can be worn on the upper arm and measures all four forms of heat flux - conduction, convection, radiation and evaporation. The accuracy of this device was compared to a whole-room indirect calorimeter.**

I. INTRODUCTION

Energy expenditure (EE) can be measured precisely in humans using direct or indirect calorimetry. Indirect calorimetry is based on respiratory gas exchange; all energy-releasing reactions in the body require oxygen, and oxygen consumption is proportional to EE. Conversely, direct calorimetry is based on heat production; all of the body's metabolic processes produce heat with little net storage, so the quantity of heat lost is proportional to EE [4]. Whole-room calorimeters based on both direct and indirect calorimetry provide accurate measurements of EE, but they require that individuals be confined to a small living space for the duration of the measurement. Other instruments (e.g. metabolic carts based on indirect calorimetry) are suitable for relatively brief, controlled settings such as a laboratory, but are not practical for measurements in free-living individuals. Thus, a practical means to accurately measuring EE in free-living individuals has been elusive. The ability to accurately and reliably measure EE in free-living individuals would be of great clinical utility in body weight management.

The gold standard to measure EE while living freely is the "doubly labeled water" (DLW) method, which is based on principals of indirect calorimetry. The process involves ingesting a dose of the stable isotopes ^2H_2O and $H_2{}^{18}O$ and then measuring the elimination of these isotopes in the urine. The difference in elimination rates of the isotopes is proportional to the magnitude of metabolic CO_2 (VCO_2) production, which is then used to calculate total oxygen consumption (VO_2) and EE [5]. This approach yields the average EE over a measurement period of 7 to 14 d, but there is no information about patterns of activity. Moreover, the high cost of the isotope, coupled with the need for mass spectrometry to analyze urine, makes DLW prohibitively costly for clinical assessment [3]. Other than the DLW approach, there are no practical means to measure free-living EE based on indirect calorimetry.

There have been few attempts to measure free-living EE based on direct calorimetry. There are four components of heat flux in the human body: 1) convection, the exchange of heat between the body and air or water molecules moving past the skin; 2) conduction, the exchange of heat between the body and materials in contact with the skin; 3) radiation, the electromagnetic exchange of heat between the body and the environment; and 4) evaporation, transfer of heat from the skin to vaporized sweat. There is currently only one sensor available commercially (SenseWear Pro Armband^{TM}, Body Media, Pittsburgh, PA) that estimates EE, in part, from measuring heat flux. This device uses what can be described as convective heat flux sensor in conjunction with three additional sensors including an accelerometer, galvanic skin response and skin temperature to estimate EE. A major limitation of this device is that it does not directly measure evaporative heat loss, which causes errors in measuring EE during exercise. The SenseWear significantly underestimates EE during walking (~7%), stepping (~18%), and cycling (~29%) [1].

A new sensor shows great potential to accurately measure EE in free-living individuals. The LifeChek® calorie sensor (MetaLogics Corporation, Minneapolis, MN) is a direct calorimeter worn on the body that measures all four components of heat flux, including evaporation. The LifeChek® measures EE using a proprietary algorithm to extrapolate the sensed local heat flux to heat flux for the entire body surface. In this paper, we describe the technical aspects of the LifeChek® calorie sensor, and present preliminary results from a validation study performed using whole-room indirect calorimetry.

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II. BACKGROUND

A. *Heat flux in the human body*

As a homeotherm, the human body maintains a nearly constant internal body temperature (core temperature) by balancing the generation of heat (from metabolic processes) with the controlled loss of heat through the processes of evaporation, convection, radiation, and conduction. At rest, the body generates a substantial amount of heat (approximately 100 Watts). To maintain body temperature at 37°C (98.6°F), heat loss to the environment is controlled by regulating blood flow to the extremities and skin. At rest, the body exchanges heat primarily via convection and radiation, although there is a small conductive component as well. At rest in thermoneutral or cool conditions, blood flow to the skin and extremities is restricted, and the body surface may be as much as 6°C (20°F) cooler than the core. During muscular contraction, approximately 80% of the energy liberated during the hydrolysis of adenosine triphosphate (ATP) is released in the form of heat; thus, the repeated muscular contractions during exercise produce a substantial amount of heat that must be dissipated to maintain core temperature. During exercise, blood flow to the skin and extremities increases; the increased blood flow to the skin facilitates flux of heat from the body, and facilitates maintenance of core temperature. During exercise or in warm ambient conditions (>35°C) convective and radiant heat loss is inadequate to maintain core temperature, so the body begins to utilize evaporative heat loss as well. Evaporation, which occurs both sensibly (i.e. sweating) and insensibly (without obvious sweating) can provide several fold greater heat loss than convection and radiation combined.

B. *Measurement of heat flux in humans*

Heat flux from the body can be quantified based on knowledge of the body surface area (BSA). By sampling at a few select locations around the body, each measured value is multiplied by a weighting co-efficient to estimate heat loss from that region of the body. The sum of all regional heat loss components is used to estimate total heat loss based on BSA.

Traditional heat flow sensors are generally based on the measurement of the temperature differential that occurs across a material due to the thermal resistance of that material. For the sensor to accurately measure the heat flow it must not add a significant insulating layer and it must lose heat from its surface in the same manner as the surface on which it is placed. Certain available heat flow sensors perform well on inanimate objects such as walls, doors, boilers, and pipes, where convective, radiant, and conductive heat loss mechanisms predominate. Such heat flow sensors are, however, inadequate for measuring heat loss from the human body, where evaporative heat loss may be substantial. Commercially available heat flow sensors are not designed for this application and are unable to reliably include the component of evaporative heat loss from the body as part of its output signal. This results in an underestimation of heat loss for two main reasons: 1) such sensors actually occlude the surface of the skin, preventing evaporation, and therefore, any moisture that does move from under the sensor evaporates from the skin surface adjacent to the sensor and not from the sensor surface itself; and 2) when used to monitor body heat loss, as the evaporative heat loss increases from the skin surface, thereby reducing the skin surface temperature, these sensors actually show a decreased heat flow.

C. *Description of the LifeChek® Calorie Sensor*

The LifeChek® calorie sensor is the first device that has taken the concept of direct calorimetry and reduced it to a practical product that can be body worn in a free-living environment. Its operating principle allows it to directly measure EE. The device is designed to be comfortably worn on the upper arm and is only slightly larger than a typical heart rate monitor (Figure 1). The device is extremely light and compact, weighing just 25 grams (35g with Velcro strap). The heat flow sensing area is connected to a self-contained electronics package (Figure 2). The unit is powered by a replaceable 3V lithium cell, providing approximately 6 months of normal operation. The output of the heat flow sensor is digitized by a 24 bit ADC under control of an 8-bit microcontroller. The

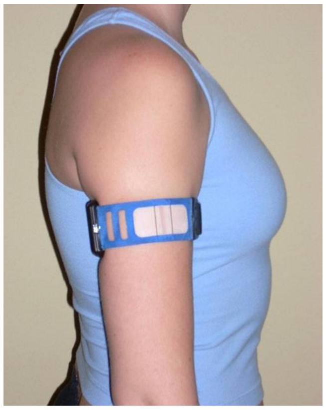

Figure 1. LifeChek® Calorie Sensor

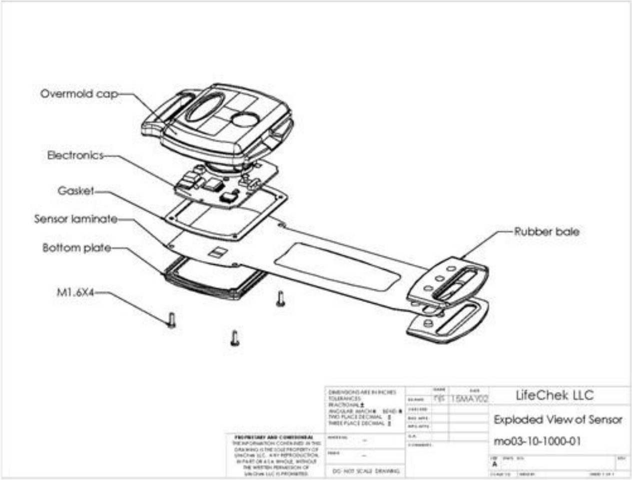

Figure 2. The LifeChek® heat flow sensor.

heat flow is measured four times per minute and the data is stored in resident 512K flash memory which provides for storage of up to 14 days of EE information. The prototype device downloads stored data via infrared to a personal computer for data analysis. The user's anthropometric data is stored on the personal computer for use in converting the single site data to whole body EE through a proprietary algorithm.

The active sensing technology of this device consists of a proprietary heat flow gauge. A heat flow gauge (HFG) works by measuring the temperature differential that develops due to thermal resistance across an insulator when heat flows through that insulator. The HFG in the LifeChek® sensor uses multiple pairs of thin foil thermocouples (TC) to measure the temperature on opposite sides of a polyimide film. These multiple pairs are produced by etching the TC foil into a U-shaped serpentine pattern and then laminating, by heat and pressure, strips of thermally insulating polyimide film placed under the outer TC and over the center TC. This results in the structure depicted in Figure 3 in which the TC pairs are positioned on the top and bottom of the insulating polyimide layer. This assembly permits the thermocouples to be worn against the skin, and can accurately measure all four forms of heat flow including conductive, convective, radiant and evaporative forms of heat transfer. Not shown in the figure, for simplification, are the thin outer layers used to seal the HFG. Thus, like flexible printed circuits, the heat flow gauge consists of metal foils sandwiched between layers of polyimide films. The gauge is approximately 25mm in length by 3.5mm in width and is 0.2mm thick. The geometry of the HFG is of critical importance in this application in order to reliably measure all four forms of heat flow. The calorie sensor's HFG has been optimized despite two competing design goals; first, the need to have a dense population of thermocouples to provide adequate signal strength, and second, the requirement for the gauge to be as small as possible in width and height so as to not occlude the skin surface, thus changing the heat flux in the sensing area, and also to allow easy migration of perspiration up and around the gauge to the top thermocouple junctions. This is critical to accurately measure evaporative heat flows.

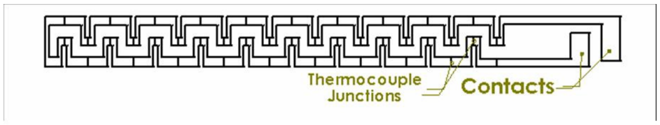

Figure 3. U-shaped serpentine pattern of the thermocouple foil.

The HFG has been integrated into the armband assembly which is manufactured using traditional flexible circuit techniques (Figure 4). Of critical important to the success of the design is the ability to place the HFG over the skin surface in this assembly and to not disrupt the normal temperature of the measurement area. A particular challenge in the development of this device was devising a method to accurately capture both sensible and insensible evaporative heat flows. As stated, in certain activity states, these flows can be a significant portion of total heat flow and therefore, the accurate measurement of evaporative losses is critical to the accuracy of any body-worn direct calorimeter. To overcome this challenge, in addition to the use of a narrow and thin HFG, a membrane has been placed over the HFG. This membrane serves to wick perspiration from the user's skin to the top of the HFG. The membrane material was chosen for particular properties, such that it mimics the skin's normal evaporative rate and does not trap moisture, or create an artificial heat sink.

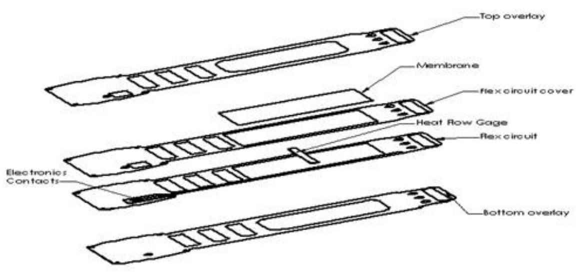

Figure 4. LifeChek® arm band assembly.

The upper arm was chosen as the site for wearing the sensor as it is close to the body's core (the best predictor of total-body heat flux) and is also convenient as the user can conceal the unit under normal clothing. This site has been validated as being highly predictive of whole body heat flux.

The device uses a simple algorithm to convert the heat flux sensed at the site of the gauge to a measurement of heat flux from the entire body surface and ultimately total EE. The measured heat flux (kcal/hr/m2) is multiplied by the body surface area (calculated from height and weight using DuBois formula) to calculate the calorie burn rate (kcal/hr). The burn rate is integrated over time to determine total calories. The device captures and stores minute-by-minute calorie expenditure which can provide data to the user or clinician such as average calorie expenditure, cumulative calorie expenditure, expenditure versus goal and a variety of other useful data points.

III. VALIDATION

A. *Preliminary validation studies*

Significant effort has been devoted to validating the sensing accuracy of this device. In-house testing has used indirect calorimetry, infrared thermography and proprietary evaporation measurement techniques to validate device accuracy in all states including at rest and in light, moderate and intense exercise sessions. Proprietary fixtures and test methods have been developed to test the HFG for heat flux measurement accuracy and to test the properties of the evaporation membrane.

One example of test data is shown in Figure 5. In this test, minute by minute EE was compared using the LifeChek® sensor vs. an indirect calorimeter. The subject rested for the first 5 minutes and then walked on a treadmill beginning at 2.5 mph at 0% grade. The pace was increased after 10 minutes to 3.0 mph and then finally after 10 minutes the grade was changed to 5%. At minute 35 the subject ceased walking and rested. A dramatic increase in EE can be seen at minute 5 with the transition from rest to walking and again at minute 25 with the grade change. This graph illustrates a fairly typical thermophysiology response during exercise and the ability of the LifeChek® sensor to accurate capture EE. As can be seen in Figure 5, although calorie expenditure begins to increase immediately upon the start of walking (as seen by the indirect calorimeter), the body stores a portion of these calories as average body temperature is increased. This can be seen in the differential of EE in the early portion of the exercise where the EE measured from heat flow is smaller. As the body warms, the heat flow from the body approaches steady state such that at the maximum activity it is equivalent to the indirect. Also, when exercise ceased at minute 35, the indirect calorimeter reflects the nearly immediate drop in EE and although there is a similar initial drop in heat production, there is a rebound as the body continue to release the stored calories well after the exercise is complete.

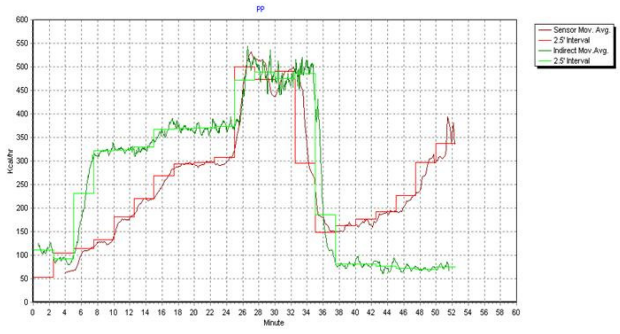

Figure 5. Comparison of EE measured by the LifeChek® sensor (red lines) and indirect calorimetry (green lines).

During this test, infrared thermography was also used to record skin temperature of the subject (Figure 6). After 10 minutes of exercise an increase in skin temperature (as seen by lighter colors in the center image compared to the left image) was found but just 5 minutes later the temperature has fallen (darker colors in final image) with the onset of perspiration causing cooling. Although skin temperature was found to be decreasing (with the onset of perspiration) at minute 20, the heat flow continued to increase verifying the sensors capability to capture evaporative losses Although minute by minute data of EE varies between the sensor and the indirect calorimeter at various times during the trial, the total EE measured in this subject was 203 kcals and 219 kcals respectively.

Figure 6.Infrared thermography during an exercise bout in a single subject. Rest (left panel), and after 10 (center) and 15 (right) minutes of exercise.

In another test, the output of the calorie sensor was compared to the production of perspiration using an in-house developed perspiration monitor (Figure 7). This monitor measured the increase in humidity of an airstream passing through a sampling chamber sealed to the skin surface. At a fixed flow rate, the change in humidity is proportional to perspiration production. As can be seen in Figure 7, the measured heat flow closely correlates to the changes in perspiration production, providing further support for the sensor's ability to accurately measure evaporative heat losses.

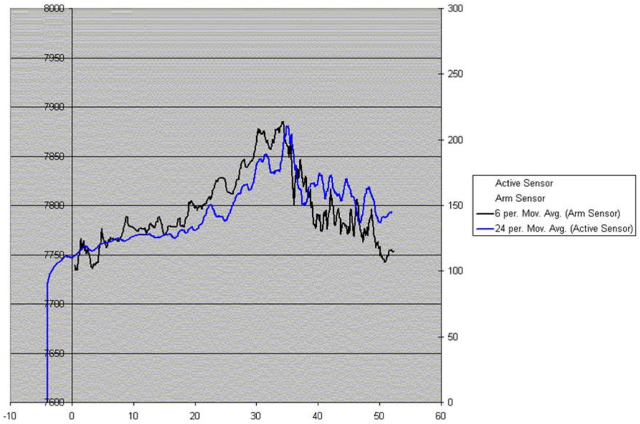

Figure 7. Comparison of heat flux measured by LifeChek ® Sensor (black line) and relative perspiration production (blue line).

In addition to internal testing, a prototype of the device (KALX monitor) has been the subject of three independent validation studies. In one trial, 20 healthy males and females were studied in a series of four modes (treadmill walking, stationary cycling, slideboarding, and bench stepping) [6]. The difference in EE between the KALX monitor and that determined using indirect calorimetry were < 1 kcal/min for most exercises, demonstrating the feasibility of this technology in measuring EE during various intensities of exercise.

B. 24 h energy expenditure

Although the preliminary validation data using indirect calorimetry during discrete exercise bouts were encouraging, the ultimate goal is to demonstrate that the LifeChek® sensor provides valid measurements over 24 hrs. Thus, we have recently performed a pilot study using a prototype of the LifeChek® sensor to determine its accuracy in measuring 24 h EE. Data were compared to EE measured using the whole-room indirect calorimetry at the University of Colorado, Denver. The room is 12 feet x 12 feet and contains a regular hospital bed, a desk, a toilet, a telephone, a flat screen TV with a DVD player, and a computer with internet access. Gas concentrations are determined from the flow rate and the differences in CO_2 and O_2 concentrations between entering and exiting air using an infrared CO_2 analyzer and paramagnetic O_2 analyzer. Values for all indices are averaged over 1-min intervals and recorded to a data file. Total daily EE are determined from measurements of oxygen consumption and carbon dioxide production based on the equations of Jequier [2].

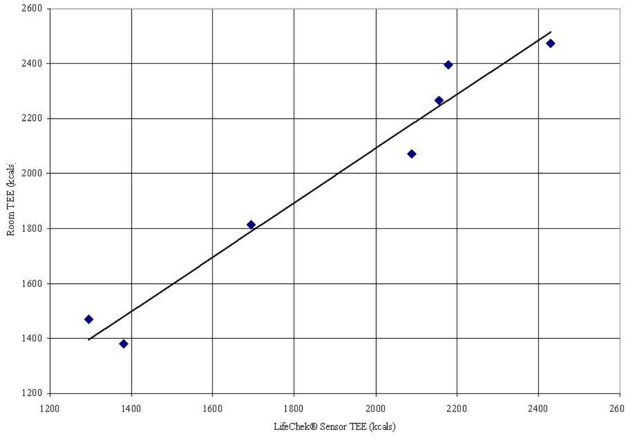

Figure 8. Association between EE measured with the LifeChek® sensor and whole room indirect calorimetry.

Seven subjects wore the LifeChek® sensor while residing in the room calorimeter for approximately 22.8 h. This group was comprised of four females and three males with a mean age of 31.8 ± 7.2 and a mean body mass index of 27.8 ± 7.9. Various activity protocols were used, which varied by subject, including 20 minute bench stepping and 60 minutes on a stationary bicycle. The mean collection period was 17.2 h with the minimum collection period of 11.3 h during the subject's stay in the chamber. Three subjects provided data for the entire collection period during the time in the chamber. Energy expenditure measured by the LifeChek® sensor, based on an average period of measurement (~17 hrs), was 1889 ± 165 kcals (mean ± SE), and EE measured by the room was 1981 ± 1655 kcals, and the measurements were highly correlated (r=0.98, Figure 8). More importantly, within subjects, EE measure with the LifeChek® sensor tracked very well with EE measured by the room calorimeter (Figure 9). Thus, we believe this device has great potential for tracking relative changes in EE within individuals.

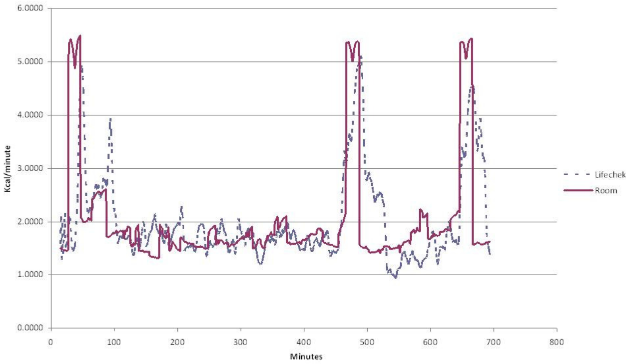

Figure 9. Example of minute to minute readings obtained with the LifeChek® sensor (dashed line) and whole room indirect calorimetry (solid line) in a single subject. The three periods of elevated EE are periods when subject was performing bench stepping.

IV. CONCLUSION

Our pilot testing demonstrates the potential of the LifeChek® calorie sensor. We are continuing with our room calorimeter validation trial, and aspire to follow this up with a validation trial in free-living humans using DLW as the "gold-standard" comparison. The LifeChek® calorie sensor will be a useful instrument in both commercial and clinical weight loss settings. It will also provide an important research tool for assessing free-living energy assessment, and will be a much less costly alternative to the doubly-labeled water (DLW) approach. Moreover, the LifeChek® monitor will provide immediate results; the DLW approach requires mass-spec analysis to determine EE.

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