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CLINICAL APPLICATION OF THERMOGRAPHY FOR ENERGY BALANCE IN ATHLETES – STATE OF THE ART AND NEW PARADIGMS

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APLICAÇÃO CLÍNICA DA TERMOGRAFIA PARA EQUILÍBRIO ENERGÉTICO EM ATLETAS – ESTADO DA ARTE E NOVOS PARADIGMAS

APLICACIÓN CLÍNICA DE LA TERMOGRAFÍA PARA EQUILIBRIO ENERGÉTICO EN ATLETAS – ESTADO DEL ARTE Y NUEVOS PARADIGMAS

Tiago Lazzaretti Fernandes[1]
(Physician)
Arnaldo Jose Hernandez[1]
(Physician)
Cyro Albuquerque[2]
(Mechanical Engineer)
Carlos Eduardo Keutenedjian Mady[3]
(Mechanical Engineer)

1. Universidade de São Paulo, Faculdade de Medicina, Hospital das Clínicas (HCFMUSP), Institute of Orthopaedics and Traumatology, Sports Medicine Group, Sao Paulo, Brazil.
2. Centro Universitário da FEI, Mechanical Engineering Department, São Bernardo, Brazil.
3. Universidade Estadual de Campinas (Unicamp), School of Mechanical Engineering, Campinas, Brazil.

Correspondence:
Tiago Lazzaretti Fernandes
Rua Dr. Ovídio Pires de Campos, 333, São Paulo, São Paulo, SP, Brazil. 05403-010. tiago.lazzaretti@usp.br

ABSTRACT

This article aims to describe the evolution of techniques that have enabled the proper application of the Laws of Thermodynamics for physical activity and athletes. The objective is to propose performance indicators to help add information to the current indices used in medicine and sports, such as the lactate threshold and maximum oxygen consumption. A number of analyses of the results obtained by the group were carried out for this purpose. Moreover, a discussion regarding which techniques would provide a better response to the measurements was analyzed. Some examples are the substitution of the treadmill running test with the stationary bicycle (known performed work), and a literature search in order to measure internal temperature more accurately. ***Level of Evidence V; Expert opinion.***

Keywords: Thermodynamics; Physical exercise; Thermography; Athletes.

RESUMO

Este artigo descreve a evolução de técnicas que possibilitaram a aplicação adequada das Leis da Termodinâmica às atividades físicas e aos atletas. O objetivo é propor indicadores de desempenho que ajudem a acrescentar informações aos índices atuais usados em medicina e nos esportes, como o limiar de lactato e o consumo máximo de oxigênio. Diversas análises dos resultados obtidos pelo grupo foram realizadas com essa finalidade. Além disso, procedeu-se à análise da discussão sobre quais técnicas proporcionariam resposta melhor às medições. Alguns exemplos são a substituição do teste de corrida em esteira pela bicicleta ergométrica (que sabidamente, pode ser usada para o trabalho), e a pesquisa da literatura para medir a temperatura interna com maior precisão. ***Nível de Evidência V; Opinião de especialista.***

Descritores: *Termodinâmica; Exercício; Termografia; Atletas.*

RESUMEN

Este artículo describe la evolución de técnicas que posibilitaron la aplicación adecuada de las Leyes de la Termodinámica a las actividades físicas y a los atletas. El objetivo es proponer indicadores de desempeño que ayuden a acrecentar informaciones a los índices actuales usados en medicina y en los deportes, como el umbral de lactato y el consumo máximo de oxígeno. Fueron realizados diversos análisis de los resultados obtenidos por el grupo con esa finalidad. Además, se procedió al análisis de la discusión sobre qué técnicas proporcionarían respuesta mejor a las mediciones. Algunos ejemplos son la sustitución del test de carrera en cinta por la bicicleta ergométrica (que sabidamente, puede ser usada para el trabajo), y la investigación de la literatura para medir la temperatura interna con mayor precisión. ***Nivel de Evidencia V; Opinión de especialista.***

Descriptores: *Termodinámica; Ejercicio; Termografía; Atletas.*

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INTRODUCTION

The body temperature has always been considered as an indicator of health. Lavoisier (1743–1794) showed that humans generate heat by a combustion process resulting in the production of carbon dioxide and consumption of oxygen[1]. VO_2 max, running economy, fractional utilization of VO_2 max and lactate threshold are used for health status, evaluation of training intensity and improving the performance of endurance in athletes [2,3]. Study of body temperature, energy balance and thermodynamics may also be useful for predictions of aerobic threshold and exercise prescriptions for health issues[2].

The Thermodynamics is usually related with thermal machines in which heat is converted into work such as in thermal power plants. Nevertheless, its applicability is general, e.g., wherever there is a disequilibrium, there is a potential to perform any work. Several research areas are based on Thermodynamics principles, Mechanical, Chemical and Environmental engineering and biological systems. This fascinating field of science is based on Four relatively simple Laws[4].

The thermodynamics is usually known because of the First Law, which states that in any energy transfer process there are no energy losses, it is conserved (usually called the energy conservation law or energy balance). Nevertheless, it cannot state some simple matters related to what process can or cannot occur and the quality of the energy. For the First Law of Thermodynamics 1 J of energy transferred as heat is the same of 1 J of performed work. A good example for this issue is the electric shower, which satisfies the First Law (almost all the electric power is converted to increase the water temperature). However, there is a decrease in the energy quality demonstrated by the Second Law – the efficiency to perform work with a thermal machine using water at 45 ºC as energy source is negligible.[5,6]

The Second Law of Thermodynamics is what define these limitations. Therefore, the energy always goes from a body with a higher temperature to a lower temperature. Moreover, 1 J of work has a higher quality than 1 J of heat. The concept behind the Second Law of Thermodynamics is the property entropy, and it is not a conservative Law. Hence, every single process is irreversible. The environment of any energy conversion process can be determined by the entropy generation or destroyed exergy (destruction of work capability).[4,7]

Because the Second Law of Thermodynamics establishes an upper limit of performed power (quality of energy conversion process), several authors are using these concepts to compare the results with sports medical performance indexes, such as maximum oxygen consumption and lactate threshold. The relation between the human body during a treadmill running test and the Thermodynamic (most related to Second Law) indexes were first performed in[9]. Results indicated that the Second Law of Thermodynamics might be used as a tool to predict athletes' performance. At this point, it was found two major problems. How to the determine the body temperature without interfering in the experiment and the precision of the equations found in the literature. The methods used to obtain the performed work in literature lead to values from 343 to 1650 W for speeds between 3.6 and 3.9 m/s, as demonstrated in Kaneko[9], which displays that the discussion on the calculation of performed work, in a treadmill running test, has not yet had an ultimate conclusion. To this aim, after a period, some studies applied several literature equations for the work and concluded that the treadmill might not be the best way to evaluate the Thermodynamic behavior of the human body[10].

Eventually, it was performed a comparison of two tests in which the power executed by the body is a known variable: bicycle stationary ergometric test and weightlifting[11]. Results indicated that the use of a stationary bicycle is the best option to establish a method to experimentally evaluate the thermal behavior of the human body[11].

The First Law of Thermodynamics applied to the human body

As states by Schrödinger [13], for human life to be possible there must be an imbalance between the body and the environment. This disequilibrium is related to chemical composition, temperature difference and even pressure difference. Therefore, there are exchanges of matter (oxygen, carbon dioxide, nutrients) and energy (heat and enthalpy) between the body and the surroundings[7,8].

To proper evaluate the human body thermal behavior it is necessary to take into account these exchanges, and according to ASHRAE [14] and other authors[7,15], the energy balance can be described according to Equation (1).

$$\frac{dU_{body}}{dt} = (M - W) - Qrad - Qconv - Hevap - \Delta Hresp$$

In this equation, the first term represents the variation of the body internal energy over time, which depends on terms that are directly or indirectly related to:

- Environmental parameters such as temperature (T_0), relative humidity (φ), and the type of radiation (solar, indoors – T_{rm}).
- The person anatomy as the body surface area[16], height, mass.
- Some personal characteristics such as the metabolism (M), which is related to oxygen consumption and carbon dioxide production to proper supply the energy demand to some activity, or performed power.
- The thermal interaction between the body and the environment such as the exchanges associated with convection (Q_{conv}) and radiation (Q_{rad}).
- Energy (enthalpy) related to the water vaporization at the skin H_{evap}.
- Modification of the composition and humidity of the inspired to expired air (ΔH_{res})

Each of these terms is measured to evaluate the energy balance properly. The unity that is used in mechanical engineering is W, but when there is a comparison between several anatomies, it is usually normalized by the surface area (W/m^2)[16], since this physical quantity is more important to heat and mass transfer than the body mass.

Experimental Procedure and Difficulties

The most common experimental tests performed to analyze the body's thermal performance are based on the treadmill or stationary bicycle tests that are regularly made for the evaluation of athletes. To obtain physiological performance indexes indirect calorimetry (respirometer) equipment is often used nowadays. With the measurements of the end-tidal PO_2 and PCO_2 and pulmonary ventilation, it is possible to estimate the energy term for the metabolic reactions (M) and the energy transferred by respiration (ΔH_{res}). The equations to these evaluations are demonstrated in.[8]

The variation of body temperature throughout the exercise directly influences the variation of the internal energy of the body over time, where c is the specific heat of the body (kJ/kgK). This term also depends on the mass and composition of the body, which can be obtained from a bio impedance balance. A more descriptive analysis may be found in[15].

The body temperature can be estimated from the internal temperature and skin temperature. The former can be obtained with an ear thermometer, or by the temperatures of the esophagus or rectum by invasive methods. The problem of the ear thermometer is that the temperature is lower than the esophagus temperature, which is closer to the central internal part of the body, and might be obtained nowadays using a digestible pill. It is important to highlight that most variation of the body temperature is in areas very close to the skin.

For the measurement of skin temperature, the most modern method is the use of thermal cameras, which had great evolution in the last years with the availability of low-cost models. Its use is increasingly being discussed in medicine, as an aid in diagnostic techniques of several pathologies. They allow obtaining images in the infrared wave range, unlike ordinary cameras where the image is captured in the visible light wave range. Any surface above 0 K emits thermal radiation in the form of electromagnetic waves, and at temperatures of usual environment conditions these waves are infrared, therefore, a thermal camera can accurately estimate the temperature distribution of surface temperature from the images.

The skin temperature is also of great importance for obtaining terms of the energy exchanged with the air by convection (Q_{conv}), with the walls by radiation (Q_{rad}), and by the evaporation of sweat (H_e). The production rate of body sweat reflects on the amount of wet surface of the body and is a necessary parameter for a correct estimation of this last term. Among the available methods, it might be obtained by the amount of water lost by the variation of the body mass throughout the exercise, or locally by checking the mass absorbed by filters papers at some body sites or by checking the skin conductance variation, which varies with the amount of sweat.

There are several definitions in the literature for the work developed during a running activity, and some difficulties are found to determine the correct work for the thermal balance, which satisfies the definitions of thermodynamics (the work to lift a weight). For the exercise on a stationary bicycle, the work can be estimated from measurements of the applied torque and rotation.

Results of previous analyses and future works

For the moment authors are formalizing the most suitable method to improve the evaluation of the thermodynamic behavior of the human body, where the mass and energy transfer between body and environment must be properly determined. The Second Law of Thermodynamics increases the number of information and, such as[8], it was possible to obtain some correlation with the training level of athletes and the quality in which they use the ATP to perform work.

A point to be emphasized is the accurate measurement of internal temperature. Results published in[12] show that the tympanic temperature may not be the best parameter to proper describe the internal temperature, although it is the least invasive of all methods. Nevertheless, methods such as esophageal, external tympanic membrane, mouth or rectum are invasive and have a slow response to the variations in body temperature[17]. The tympanic temperature was adequate regarding the invasion criteria, but it may be influenced by the ear skin temperature and environmental temperature[17]. Eventually, it was studied a new method related of a pill which is a gastrointestinal temperature measurement with an optimal time to be taken of 6h after the tests, because it may be influenced by simple things such as water ingestion[17].

Finally, the relation of internal temperature with the performance of athletes was extensively analyzed in[1], where it was possible to conclude that in a day with high temperatures and high humidities an extra-careful must be taken into account to ensure that there is no loss of performance. This analysis is also very extensive performed using computational models to predict thermal comfort conditions. Where the worst-case scenario is environments with high temperature and high relative humidities, therefore, even at rest conditions the body may achieve hyperthermia.[18]

Sports medicine has its parameters to measure the training capability for several training levels sportsman properly. The maximum oxygen consumption is one of the most common, and a detailed study of the lactate threshold is either utilized for this purpose and depends on training intensity and aerobic capacity of the runners.[2]

In conclusion, this research field is in state of the art with new apparatus such as thermography to measure skin temperature, the amount of sweat in the skin (the phenomena controlled by the body to increase the energy transfer to the environment). The internal temperature has been proven to be difficult to properly evaluate only with traditional methods. The remaining problem is the gradient of temperature between the core, and the skin which is highly accurate represented by.[15] From these measurements, it is possible to use the stationary bicycle to have the performed work[11,12] and properly evaluate the traditional models of heat and enthalpy transfer to the environment[15] which are highly validated for basal conditions. Eventually, the relations of different researchers of several fields, mechanical engineers (thermodynamic and heat and mass transfer area) and medical doctors (from sports and orthopedic field) have been increasing the relation with two areas with similar objectives, although with a completely different language. The main objectives are to evaluate a person during physical activities and compare the usual performance indices to the Second Law based one.

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