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Theoretical modeling of time-dependent skin temperature and heat losses during whole-body cryotherapy: A pilot study

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ABSTRACT

This article establishes the basics of a theoretical model for the constitutive law that describes the skin temperature and thermolysis heat losses undergone by a subject during a session of whole-body cryotherapy (WBC). This study focuses on the few minutes during which the human body is subjected to a thermal shock. The relationship between skin temperature and thermolysis heat losses during this period is still unknown and have not yet been studied in the context of the whole human body. The analytical approach here is based on the hypothesis that the skin thermal shock during a WBC session can be thermally modelled by the sum of both radiative and free convective heat transfer functions. The validation of this scientific approach and the derivation of temporal evolution thermal laws, both on skin temperature and dissipated thermal power during the thermal shock open many avenues of large scale studies with the aim of proposing individualized cryotherapy protocols as well as protocols intended for target populations. Furthermore, this study shows quantitatively the substantial imbalance between human metabolism and thermolysis during WBC, the explanation of which remains an open question.

Introduction

Whole-body cryotherapy is considered a non-intrusive complementary physical therapy that involves placing the human body in a chamber cooled to about −110 °C for a short duration under three minutes. The objective is to stimulate human body reflexes during the resting state in conditions of extreme cold. Cryotherapy generates thermal shock and, in a manner similar to the reset function of computers, activates a wide range of survival biomechanical and biochemical reactions.

Research into the benefits of cryotherapy is extensive. We do not undertake an exhaustive review of literature, but we refer to some of the more significant ones. Several review articles summarize the current understanding of cryotherapy benefits, comprising three main areas of study: sports activities, health and wellbeing [1–5].

In the sports activity field, WBC is usually used to accelerate the recovery process of muscle injury after exercise by limiting inflammatory response and muscular damage due to tissue oxidation [6,1,7–10]. In the health and medicine research field, WBC has mainly comprised body thermal responses to cold temperatures [11–17]. A small number of studies have focused on the influence of WBC on hematological parameters [18,19], pain prevention [20], and rheumatology diseases [21,22]. Cryotherapy benefits have also been found to be important in the fields of neurology and psychiatry. Indeed, due to anti-inflammatory/antioxidative effects, as well as body function effects (i.e. hormonal and lipid changes caused by low temperatures), cryotherapy may play an important role in the modulation of the physiological or pathological processes [23,24].

Even if these studies attest to the efficacy of WBC, current understanding of its effects on human subject remains poor. The conclusion of a recent study [25] indicates it is necessary to establish optimal cooling for appropriate skin temperature responses. Costello et al. [26] well summarized the situation in the field of cryotherapy research by asking the question "what is the optimal modality, temperature and duration required to elicit the

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physiological response?". We believe that the answer ineluctably leads to an inquiry into what exactly happens during thermal shock. Are there thermal laws governing the skin temperature evolution during hypothermal shock which could deepen our understanding of the relationship between both metabolism and thermolysis mechanisms?

It is in this spirit that we have developed a theoretical model for the purpose of generating data and increasing our understanding of what occurs during these 2–4 min when human body faces extremely low temperatures.

The hypothesis

The authors have developed a mathematical model and have hypothesized that this model represents a powerful means to explore the time-dependent body thermal shock during a whole-body cryotherapy session. The purpose of this hypothesis is two-fold. First, because research is lacking in this area, the primary goal is increase our understanding of skin thermal responses to drastic reductions in ambient temperature which may initiate further studies on metabolic processes during thermal shock. Furthermore, a mathematical model represents a strong predictive tool in designing cryotherapy protocols.

Evaluation of hypothesis

In human thermal balance, heat produced by metabolism exactly compensates the heat losses caused by the thermolysis process (radiation, convection, conduction, perspiration). Because cryotherapy involves early stage immersion in extreme cold surroundings and because test subject in our study wore nothing but necessary safety equipment including a surgical mask, socks and shoes, one can reasonably conclude that heat losses are due only to both radiative and convective events. Thus the time-dependent total thermal flux Φ_{tot} emitted by the body during a cryotherapy session can be expressed by:

$$\Phi_{tot}(t) = \Phi_{conv}(t) + \Phi_{rad} \quad (1)$$

Replacing the convective and radiative surface heat fluxes by their respective analytical expressions leads to the integral formulation of the global body heat flux.

$$\Phi_{tot}(t) = \int\int_S h_c(T(t)_S - T_\propto)dS + \int\int_S \sigma\epsilon(T(t)_S^4 - T_\propto^4)dS \quad (2)$$

where T_S is the surface temperature, the surrounding temperature is $T_\propto$, the skin emissivity is $\varepsilon = 0.98$ and $\sigma = 5.67 \cdot 10^{-8}\ W/m^2K^4$ is the Stefan-Boltzmann constant.

The convective heat transfer coefficient is also skin temperature dependent and can be satisfactorily evaluated from empirical laws available from both laminar and turbulent flows with uniform heat flux density as thermal condition [27]:

$$h_c = \frac{0.0257}{H_b}\left[0.825 + 7.08(T(t)_S - T_\propto)^{1/6}H_b^{1/2}\right]^2 \quad (3)$$

where H_b is the body height.

Because the complex 3D human body is a highly heterogeneous medium from a thermal viewpoint, the present scientific approach can equally be applied to specific targeted body zones (to handle a local dermatological pathology for example) or to the whole body. In this study, we consider only the whole body, meaning that the parameters used are averaged over the whole body.

The main proposition that underlies the present approach is that the body can be considered to be a thermal system as measured by skin temperature. In this way, the time-dependent skin temperature is strongly linked to the balance between thermogenesis and thermolysis processes. Because cryotherapy involves applying a sudden thermal constraint to the body, the main thermal boundary condition to which the skin is submitted acts like a Dirac delta thermal function. In the time domain, exploring the time-response of both metabolic and heat losses requires the determination of their own time constants. This is made possible by writing the changing skin temperature function as follows:

$$\frac{T_S}{T_0} = \left[\left(1 - e^{-\frac{t}{\tau 1}}\right) + e^{-\frac{t}{\tau 2}}\right] \quad (4)$$

where T_0 is the skin temperature, body at rest.

The term $\left(1 - e^{-\frac{t}{\tau 1}}\right)$ corresponds to the internal heat production by the metabolism in extremal atmosphere while $e^{-\frac{t}{\tau 2}}$ refers to the convective and radiative thermolysis losses during the cryotherapy session. Each of these mathematical formulations that is to say each of the antagonistic actions (thermogenesis, thermolysis) has its own time constant called τ1, 2. One may consider that these time constants depend on physiological parameters peculiar to every individual. For example, for heat losses, the corresponding time constant should be mainly dependent on the body mass index (BMI) because adipose tissues act as a thermal resistance within the body [28].

The skin cooling biophysical process being a continuous one in cryotherapy, the following mathematical criteria have been considered for the mathematical model:

- No break of slope (continuity of tangents) in the skin temperature evolution.
- No inflexion point in curves on the temporal interval of study

$$\begin{cases} \left.\frac{\partial Ts}{\partial t}\right|_{t-dt} \cong \left.\frac{\partial Ts}{\partial t}\right|_{t+dt} \\ \frac{\partial^2 Ts}{\partial t^2} < 0 \end{cases} \quad (5)$$

Because this study is a preliminary one without statistical analysis, we chose to study a single subject. The objective is to show the coherence of the present approach, with the aim of extending it subsequently to a representative sampling of a given population. The subject was a male aged 25 years, size 1.75 m, weight 67 kg and 11% BMI. The subject underwent a medical examination and was declared healthy and not under medication. Written consent was obtained after the experimental protocol was explained.

For reasons of convenience and because the extreme temperature value does not inhibit the theoretical approach used, the study took place in a pre-chamber of cryotherapy at −60 °C, for a duration of 3 min. The measurement tool used for the experimental skin temperature study was a Flir SC1000 camera. Thermal imaging [29–31] was taken every 30 s during the cryotherapy session as shown in Fig. 1. It can be easily seen the cooling of the skin and its heterogeneous character. Preservation of a relatively constant internal body temperature independent of the external temperature is highlighted increasing time, where trunk temperatures are seen to be higher than that of limbs. Because the thermal imaging camera gives temperature readings for each pixel p_j of the entire thermal image, the average whole body average skin temperature is obtained when the cutaneous surface is divided in closed polygonal surfaces S_i from the relation:

$$Ts = \frac{\sum_1^n Si.\left[\frac{\sum_1^p (pjTj)}{\sum_1^p Tj}\right]}{\sum_1^n Si} \quad (6)$$

During post-treatment we obtained the average skin temperature over 180 s and compared these results with the results of the mathematical model as shown in Fig. 2. Good agreement is observed between the experiment and the model results, the maximum relative error being less than 6.5%. This proves that it

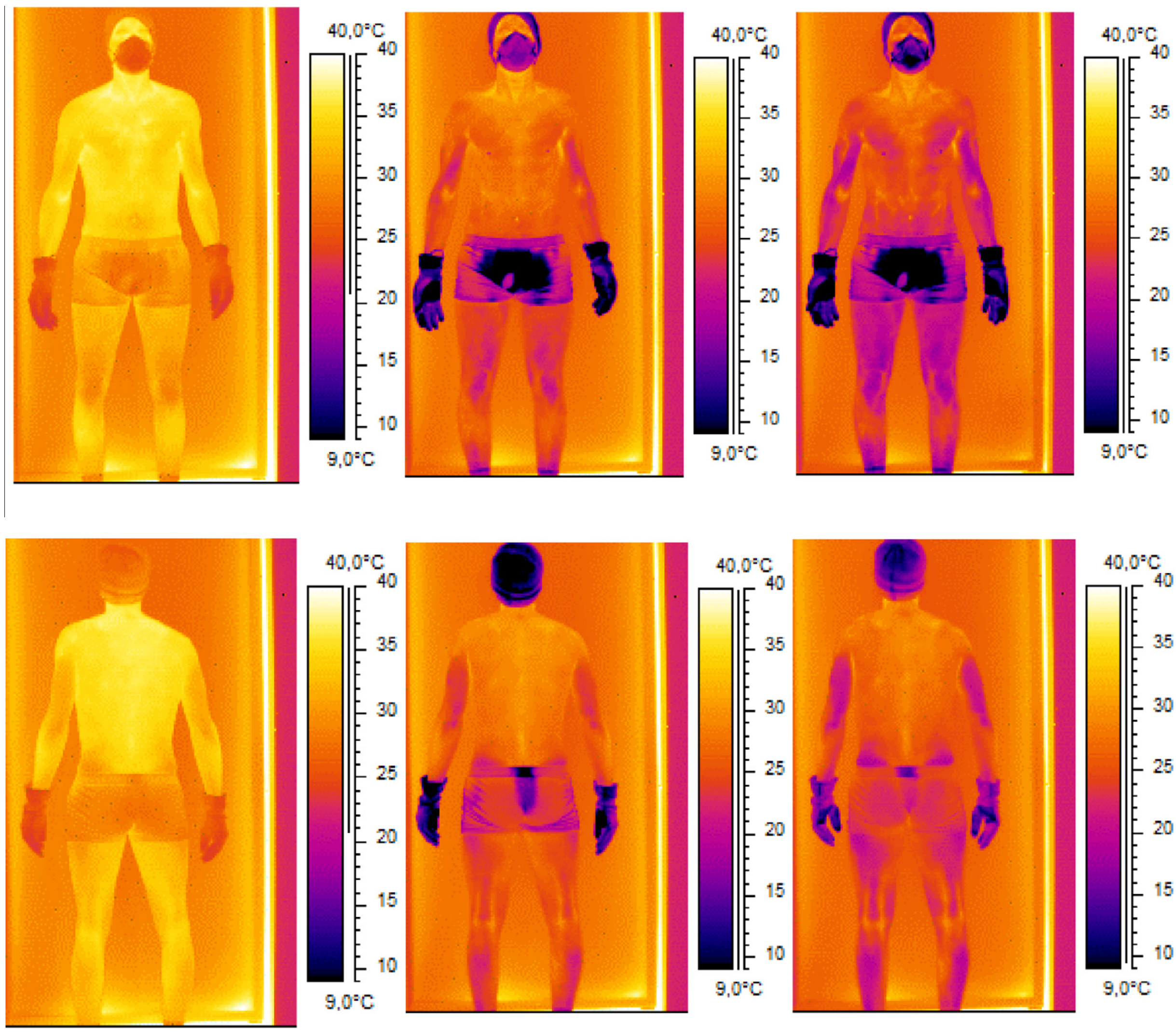

Fig. 1. IR Thermographies: before (left column), 1 min 30 during (center column) and immediately after WBC (right column).

is possible to mathematically model with a relatively high precision the transient behavior of an object as complex as the human body, from the point of view of its cutaneous temperature.

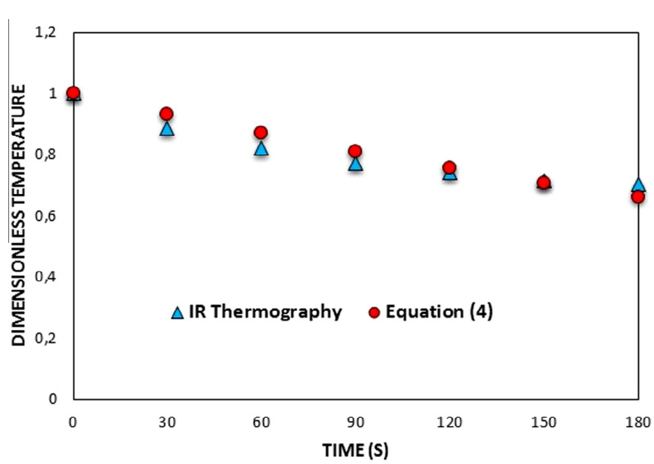

Fig. 2. Evolution in time of the average whole body skin temperature during WBC: IR Imaging versus mathematical modeling.

From mathematics to medicine

In the human thermal equilibrium state when the body is resting at ambient temperature, the metabolism compensates the heat dissipation. Mathematically, that means that the corresponding time constants are equal ($\tau_1 = \tau_2$). During a thermal shock inducing an imbalance between the thermogenesis and the thermolysis actions, the smaller a time constant is, the more important is the action on which it depends. In the present study, the mathematical analysis indicates that $\tau_1/\tau_2 = 17.5$. This implies that the metabolism is incapable of withstanding strong thermal decreases. This is a fight lost beforehand and in spite of vasoconstriction which acts as a barrier against the cold, the internal core temperature will ineluctably fall, mainly due to thermal conduction within human tissues.

Remark: In this preliminary study, we chose to consider the cutaneous temperature on the whole body surface meaning that the time constants τ_1 and τ_2 are relative to average thermogenesis and thermolysis phenomena. Obviously the mathematical model can be applied to specific parts of the body such as trunk, limbs or selected muscle groups. In such cases what will differ from the present study are the values of the time constants and particularly their ratio which will give indications onto the weighting of both thermal effects in particular zones of the human body.

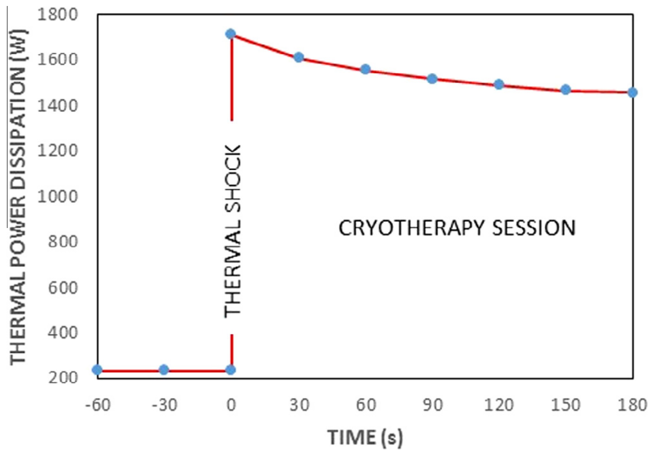

Fig. 3. Whole body thermal dissipation during WBC.

Here mathematics is a powerful tool that contributes to our understanding what happens during whole-body cryotherapy. For example, it seems convenient to analytically quantify the thermal power dissipated by the subject during the cryotherapy session. For this purpose, combining Eqs. (2) and (4) leads to the expression of the thermal power dissipated by the subject:

$$\Phi(W) = h_c S\left(T_0\left[\left(1 - e^{-\frac{t}{\tau 1}}\right) + e^{-\frac{t}{\tau 2}}\right] - T_\infty\right) + \sigma\epsilon S\left(T_0^4\left[\left(1 - e^{-\frac{t}{\tau 1}}\right) + e^{-\frac{t}{\tau 2}}\right]^4 - T_\infty^4\right) \quad (7)$$

where S is the body surface area (BSA) calculated with the following expression [32] from the knowledge of both weight and height of the subject. It is found that the subject's BSA is 1.75 m^2.

$$BSA = 0.000579479\, W^{0.38} H_b^{1.24} \quad (8)$$

The corresponding thermal power time-evolution is shown in Fig. 3. At rest, before the cryotherapy session, the regulation of heat loss and heat production to maintain core temperature within a limited range involves a continuous constant thermal waste of 232W according to the model developed (Eq. (7)). Entering the cryotherapy chamber at −60 °C, the fall in skin temperature during the thermal shock precipitates thermoregulation responses, the most spectacular of them being the drastic gap in the dissipating thermal power increasing by more than 700%. If radiation is found to be the dominant mechanism of heat loss before the WBC session (63%), it falls in a drastic way during the WBC session to reach a 38% average value. Fig. 3 shows obviously that the metabolism (hypothalamic temperature) is not predisposed to compensate for such heat losses. What happens exactly when the body is suddenly submitted to this aggressive drop in temperature? How does the body react to this immediate event? Is there a real metabolism inertia? Moreover, even if human brain regions that respond to changes in skin temperature have been identified [33], no study in literature has specifically investigated the involvement in human thermoregulation of the brainstem [34]. The answer to all these questions remains to be determined.

Conclusion

We have proposed a mathematical model based on the hypothesis that the human thermolysis as measured through skin thermal behavior can be thermally modelled by the sum of both radiative and free convective heat transfer functions. We have compared results of the mathematical model to the results of a single WBC session, with excellent agreement between them. The validation of the scientific approach and the obtaining of temporal evolution thermal laws, both on skin temperature and dissipated thermal power during the thermal shock set the stage for large-scale modeling with the aim of proposing individualized cryotherapy protocols as well as protocols intended for target populations. Furthermore, this study shows quantitatively the substantial imbalance between human metabolism and thermolysis, the explanation of which remains an open question.

Conflict of interest

The authors declare that they have no conflict of interest on the content of this paper.

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