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Should whole body cryotherapy sessions be differentiated between women and men? A preliminary study on the role of the body thermal resistance

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ABSTRACT

The aim of this study was to investigate how body thermal resistance between sexes evolves over time in the recovery period after a WBC session and to show how this parameter should be considered as a key parameter in WBC protocols. Eighteen healthy participants volunteered for the study (10 males and 8 females). Temperature (core and skin) were recorded pre- and post (immediately and every 5 min until 35 min post) exposure to a single bout of WBC (30 s at −60 °C, 150 s at −110 °C). From both core and skin temperatures a bio-heat transfer model was applied which led to the analytical formulation of the body thermal resistance. An unsteady behavior presenting a similar time-evolution trend in the body insulative response is shown for both females and males, possibly due to the vasodilatation process following an intense peripheral vasoconstriction during the extreme cold. Females present a 37% higher inner thermal resistance than males when reaching an asymptotical thermal state at rest due to a higher concentration of body fat percentage. Adiposity of tissues inherent in fat mass percentage appears to be a key parameter in the body thermal resistance to be taken into account in the definition of appropriate protocols for males and females. The conclusions of this preliminary study suggest that in order to achieve the same skin effects on temperature and consequently to cool efficiency tissues in the same way, the duration of cryotherapy protocols should be shorter when considering female compared to male.

Introduction

Whole-Body Cryotherapy (WBC) is a widely used treatment to help alleviate muscle soreness, depression, rheumatic conditions, ankylosing spondylitis, inflammatory symptoms and also to contribute to enhance muscular recovery [1,2]. In sport medicine, the use of cryotherapy has become widespread in recent years, and numerous studies in the literature have investigated the benefits of cryotherapy for athletes [3–5]. However, upon critical examination of most of these studies concerns over the empiricism of the protocols used, especially concerning relative dosage, temperature and duration tend to arise. Given that WBC may have many methodological issues it is surprising that these protocols are not differentiated between the populations studied, particularly with regard to the sex of the participants.

WBC consists of exposing patients to extreme cold air (−110 °C) in minimal clothing, during a short time duration (2–4 min). The thermal shock monitored by skin peripheral thermoreceptors induces complex thermoregulation responses via the central nervous system to maintain constant the temperature of vital organs raising physiological barriers against the extreme atmosphere [6]. The skin which is the largest organ of the body is the link between internal tissues and the environment. The dynamics of skin temperature during WBC depends on two factors, the thermal gradient between body and external environment and tissues capacity to attenuate the heat losses from the body's core to the skin. These two factors are subject to modification when the body is exposed to such an extreme temperature. The latter factor is more complex to evaluate because it takes into account numerous elements such as deep tissues adiposity, skin and muscle blood flow; which ultimately contribute to the thermal resistance. This thermal resistance expresses the thermal insulation of human tissues and is inversely

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proportional to thermal conductivity. The higher the thermal resistance, the greater the insulative response is and given that tissue cooling and transfer depends on several factors relative to sexual dimorphism (body fat), it may seem prudent to suggest that males and females insulative capacity may differ. The difference in body fat, which acts as insulation, ultimately may increase heat storage. Theoretically, the more vasoconstriction occurs due to such a cold exposure, the greater the magnitude in change of skin temperature. The change in skin temperature following WBC relative to sexual dimorphic differences has received little attention in the literature [7,8]. Effectively, the paucity of data in this field begs the question of how do sex related differences affect thermal resistance after WBC?

Therefore, the primary aim of this study was to investigate how the thermal resistance between males and females alters during the rewarwing period after a WBC session. A subsequent secondary aim of this study was to apply a bio-heat transfer mathematical model to test the hypothesis and to obtain a predictive blueprint of appropriate WBC protocols between sexes [9].

Hypothesis

In view of the lack of research on the gender influence on the WBC protocols, the aim of the current study was to investigate how body thermal resistance between sexes evolves over time in the recovery period after a WBC session and to show how this parameter should be considered as a key parameter in WBC protocols. It was hypothesized that adiposity of tissues inherent in fat mass percentage appears to be a key parameter in the body thermal resistance to be taken into account in the definition of appropriate protocols for males and females.

Methods

For the sake of conciseness, the reader is directed to a recent article for the details of the experimental, medical and administrative procedures of the current study [10]. Briefly, ten healthy young male (age 27.7 ± 6.9 years, height 1.82 ± 0.07 m, body mass 78.8 ± 13 kg, lean mass 68,5 ± 8,6 kg, body fatness 13.7 ± 6.9%, body surface area (BSA) 1.9 ± 0.1 m^2, BSA to mass ratio 2.5 ± 0.1 cm^2/kg) and eight young female (age 27.6 ± 6.3 years, height 1.63 ± 0.08 m, body mass 62.5 ± 7.7 kg, lean mass 46,1 ± 7 kg, body fatness 26.2 ± 5.4%, body surface area (BSA) 1.6 ± 0.1 m^2, BSA to mass ratio 2.6 ± 0.1 cm^2/kg) were recruited for the present study. Mean core (T_c) and skin (T_{sk}) temperatures for both male and female volunteers groups are given in Table 1. For this purpose, core (rectal) temperature was recorded after the participants self-inserted a thermistor (Grant Instruments, Cambridge, UK), ~10 cm beyond the anal sphincter. Skin temperature was recorded using a FLIR Thermal Imaging Camera (E40BX FLIR systems, Dandeyd, Sweden).

The study was approved by the Moulton College Human Research Ethics Committee and, in accordance to the Declaration of Helsinki, participants were informed of the requirements of the study prior to signing a consent form. Moreover, each participant also completed a medical consent form and declared that they were free from medical conditions including Raynaud's phenomenon and other cold sensitivities, heart conditions, claustrophobia, and allergy to adhesive tape.

Following a safety briefing from the chamber (Cryogenic chamber; JUKA Poland) operators, participants were required, in pairs, to enter the antechamber for 30 s at −60 °C, and transferred through an internal door to the main chamber for 2 min at −110 °C [10]. Following WBC exposure, participants transferred immediately to the adjacent laboratory to capture the post WBC data.

Table 1
Core (Tc) and skin (Tsk) temperatures of study participants (mean and SD) in the rewarming after −110 °C WBC.

Time (min)	0	5	10	15	20	25	30	35	∞
FEMALES									
Mean Tc (°C)	37.5	37.5	37.5	37.4	37.3	37.3	37.3	37.2	37.3
SD (Tc)	0.3	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.3
Mean Tsk (°C)	19.61	27.24	28.98	30.03	30.79	31.16	31.48	31.76	33.18
SD (Tsk)	2.40	1.26	0.50	0.21	0.28	0.22	0.14	0.19	0.41
MALES									
Mean Tc (°C)	37.5	37.5	37.4	37.3	37.3	37,2	37.1	37.1	37.4
SD (Tc)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mean Tsk (°C)	22.19	28.90	30.45	31.19	31.74	32.02	32.33	32.52	33.52
SD (Tsk)	2.29	1.58	0.91	0.62	0.60	0.46	0.42	0.42	0.59

Results

The thermal resistance of the human body is difficult to estimate because of complex anatomical and physiological factors. In the formulation used, the thermal resistance depends on the unsteady heat storage level and also on the moving boundary between deep tissues and skin, namely due to vasodilatation. The bio-heat transfer model is based on an electrical analogy in which heat flux density is associated with electric current, temperature difference with potential difference and electrical resistance with thermal resistance (Fig. 1). In such a way, the thermal resistance (R_b) takes into account both the tissues resistance between body core and skin (R_{tissue}) and the blood flow thermal resistance (R_{blood}). The corresponding core-to-skin conductance combining these parallel resistances can be expressed as [11]:

$$\frac{1}{R_b(t)} = \frac{1}{R_{tissues}} + \frac{1}{R_{blood}(t)} \quad (1)$$

The thermophysical parameter that characterizes the propensity of a material to transfer heat is thermal conductivity. For example, the conductivity of fat is 0.21 W/mK while that of blood, considered as the heat transfer fluid of the human body, is 0.52 W/mK. The ratio between these values shows that, even if blood and the associated induced actions of vasoconstriction and vasodilation have a major effect on the body's thermal response to a thermally extreme atmosphere, fat tissues nonetheless seem to have a significant effect [12,13].

Thermal analysis

Bio-heat transfer modeling of the human system aims to calculate the properties of heat transfer thermal exchanges between the human body and its environment, on the basis of a general heat balance [11]. At rest following a cryotherapy session (without conduction, evaporation), the heat balance is maintained when the rate of heat production φ_{met} (metabolism) is equal to the heat lost by radiation φ_{rad}, convection φ_{conv} and respiration φ_{resp} (Fig. 1) provided that the storage effects are neglected, which can be assumed for a low variation of core (rectal) temperature.

The human body can be considered as a weakly unsteady thermal system so that the conservation of the thermal rate is satisfied leading to the following set of equations:

$$\begin{cases} \varphi_{met}(t) = \varphi_{conv}(t) + \varphi_{rad}(t) + \varphi_{resp}(t) \\ \varphi_{met}(t) = \frac{(T(t)_c - T(t)_{Sk})}{[BSA]R_b(t)} \end{cases}$$

where T_c is the core temperature, T_{Sk} is the skin temperature, BSA is the Body surface Area and $\varphi_{resp}(t)$ is the sum of latent respiration heat loss and dry respiration heat loss. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) rules give the following equation for total respiratory heat loss [14]:

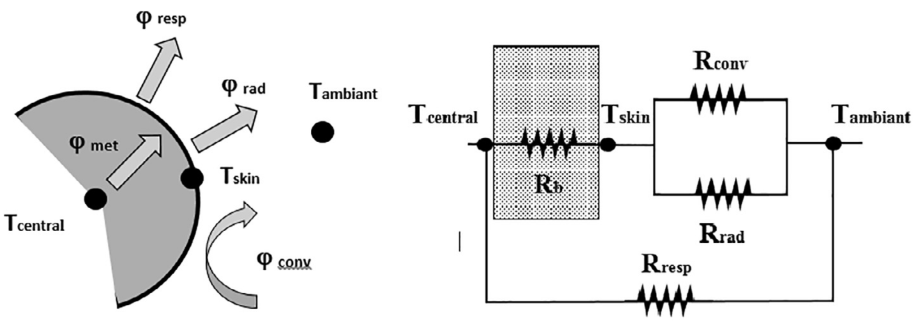

Fig. 1. synopsis of the bio-heat transfer process and corresponding electrical analogy (T, temperature; φ_{met} heat production (metabolism); φ_{rad}, heat lost by radiation, φ_{conv} by convection and φ_{resp}byrespiration; R, thermal resistance).

$$\varphi_{resp}(t) = \varphi_{met}(t)[0.0014(34-T_a) + 0.0173(5.87-P_{wv})]$$

where $T_a$is the ambiant temperature (room temperature is 20 °C) and P_{wv} is the water vapour pressure.

Deduced from the Antoine's equation [14] and introducing the relative humidity ϕ ratio between prevailing partial pressure of the water vapour and the saturated water vapour pressure, the water vapour pressure is given by:

$$P_{wv} = 10\phi\exp\left(18.956-\frac{4030.18}{T_a + 235}\right)$$

We estimated a standard rate of humidity $\phi = 40\%$ corresponding to an ideal thermal comfort level in indoor surroundings.

Under these conditions it is found that $P_{wv} = 0.935kPa$. Reporting this value and introducing an ambient temperature give:

$$\varphi_{resp}(t) = 10.5\%\varphi_{met}(t)$$

This value is very close to those already reported in literature estimating that the respiration heat loss is typically in the order of magnitude of 10% of the total heat loss for body at rest [15].

The Newton and Boltzmann laws are used for the definition of both convective and radiative heat losses and are expressed as:

$$\varphi_{conv}(t) + \varphi_{rad}(t) = h_c(t)(T(t)_{Sk}-T_a) + \sigma\varepsilon(T(t)_{Sk}^4-T_a^4)$$

where h_c is the free convective heat transfer coefficient, $\sigma$is the constant of Stefan-Boltzmann ($\sigma = 5.67\ 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}$) and $\varepsilon$is the skin radiative emissivity whose value is 0.98.

Introducing Newton and Boltzmann laws in the bio-heat transfer modelling equations leads to the following set of equations:

$$\begin{cases} (100-10.5)\%\varphi_{met}(t) = h_c(t)(T(t)_{Sk}-T_a) + \sigma\varepsilon(T(t)_{Sk}^4-T_a^4) \\ \varphi_{met}(t) = \frac{(T(t)_c - T(t)_{Sk})}{[BSA]R_b(t)} \end{cases}$$

Combining these equations leads to the final expression of the thermal resistance which is the main parameter in the evaluation of the insulative response of subjects to whole body cryotherapy:

$$R_b(t) = \frac{0,895(T(t)_c-T(t)_{Sk})}{[BSA][h_c(t)(T(t)_{Sk}-T_a) + \sigma\varepsilon(T(t)_{Sk}^4-T_a^4)]}$$

The transient 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 [16]:

$$h_c(t) = \frac{0.0257}{H_b}[0.825 + 7.08(T(t)_{Sk}-T_a)^{1/6}{H_b}^{1/2}]^2$$

where H_b is the body height. The Body Surface Area (BSA) is deduced from the following correlations for both males and females [17]:

$$[BSA]_m = 0.000579479W^{0.38}{H_b}^{1.24}$$

$$[BSA]_f = 0.000975482W^{0.46}{H_b}^{1.08}$$

where W is the body mass. The relative uncertainty in the estimation of the thermal resistance can be calculated as given:

$$\frac{\Delta R_b}{R_b} = \frac{\Delta T_c + \Delta T_{Sk}}{T_c-T_{Sk}} + \Delta T_{Sk}\left[\frac{2h_c + \sigma\varepsilon(T_{Sk}^3 + T_a^3)}{h_c(T_{Sk}-T_a) + \sigma\varepsilon(T_{Sk}^4-T_a^4)}\right]$$

Combining both experimental errors in skin and core temperatures leads to an average relative error in the calculation of Rb of 3.04% for males and 3.17% for females.

The evolution in time of the thermal resistance is highlighted in Fig. 2 where the relative standard deviation (SD) is included too. SD evolution reflects that over time in the rewarming period, the participants thermal states became more stabile and as a result more homogenized. To better illustrate the direct effect of the thermal resistance when immersed in an extremely cold atmosphere, the temporal changes in skin temperature are also shown in Fig. 2. It clearly appears that whatever the sex these two parameters (T_{sk} and R_b) evolve in an inverse proportional manner. The lower the thermal resistance, the higher the skin temperature rise, showing that thermal resistance, as in any thermal system, is opposed to internal heat diffusion from the centre to the periphery. During rewarming, one observes that the metabolic heat is moved to periphery during the vasodilatation process. However, this process takes a long time to set up because after 35 min the state of thermal equilibrium at rest is not reached. This observation is similar to the conclusions drawn of previous work [18], showing that vasoconstriction is a phenomenon that persists long after exposure to cold, more pronounced among women who generally have in the cold a more extensively vasoconstricted periphery [19]. The combination between vasodilatation and intrinsic thermal resistance of tissues acts mathematically and during the unsteadiness, and for both male and female, as

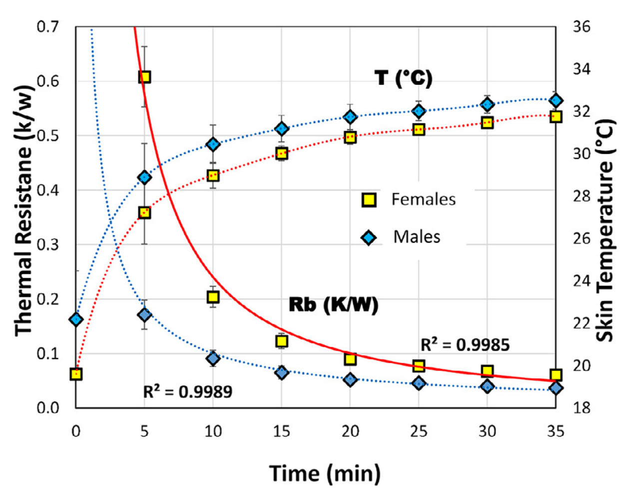

Fig. 2. Time-evolution of the Thermal Resistance R_b (left scale) and skin temperature T_{sk} (right scale) for males and females in the rewarming after −110 °C WBC.

a negative power law behaviour $R_{b(female)} = 4.379t^{-1.26}$ and $R_{b(male)} = 0.785t^{-0.89}$ during the transient. Nevertheless, whatever the duration of the experiments, the thermal resistance for females is greater than that of males, which may be due to the relative sex differences in fat tissue/adiposity.

The thermal resistance is found to have a constant value about 0.03 K/W with no mention to the anatomical sexual dimorphic differences between the sexes [20]. Therefore, the major findings of the present study's thermal analysis is that the thermal resistance can become unsteady, especially in response to thermal stress due to the vasodilatation process in the case of rewarming. Its evolution is strongly time-dependent especially at first times and seems to reach an asymptotical value increasing time. Ultimately we have shown that the value of the thermal resistance at rest depends on the sex of the participant. Indeed, the calculations performed when the participants were in a rested state, prior to cryotherapy treatment lead to the following calculated assumptions:

$$\begin{cases} \lim\limits_{t\to\infty}(Rb)_{male} = 0.027K/W \\ \lim\limits_{t\to\infty}(Rb)_{female} = 0.037K/W \end{cases}$$

The comparison in the thermal resistance key parameter between male and female indicates a 37% difference at rest.

The thermal analysis raises the question of body composition and the relative influence this parameter has on the thermal resistance. This may certainly be true when considering the assumption of fat mass percentage as a parameter for this bio heat transfer model of thermal resistance, on the basis of previous work suggesting that there could be a direct relationship between the adipose thickness and required cooling time [21].

Statistical analysis

All statistical analyses were performed using STATISTICA *(data analysis software, version 13.0.0)* Normality of raw data was checked in each group (male and female) using the *Shapiro-Wilk* test. Pearson's correlation coefficients were calculated between body fat mass and the body resistance at each time of assessment (from Min 5 to Min 35).

For conciseness, only 35-min post WBC was considered in Fig. 3, where fat mass was found to be significantly and positively correlated with thermal resistance in males ($r = .84$; $p = .002$)). In female participants, this association also was positive but did not reach the level of statistical significance ($r = .25$; $p = .558$). It is assumed that this level of statistical significance would certainly have been achieved if the number of female subjects had been higher (only 8 subjects for this study). This is in accordance with previous studies showing that fat mass is positively related to tissue insulation [22]. For instance, subjects with high body fat percentage are capable of enduring lower ambient temperatures without significantly increasing heat production [23]. However, our findings suggest that sex could have an influential moderating effect.

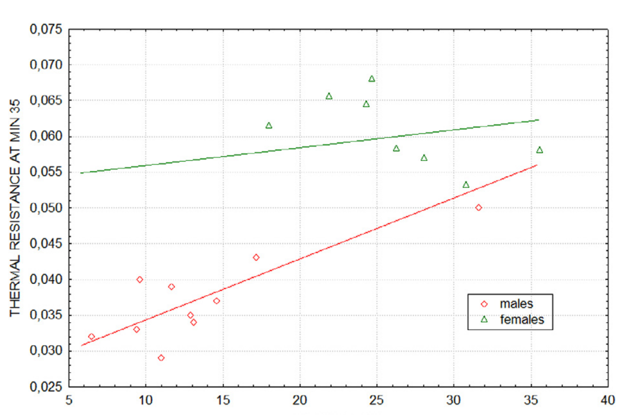

Fig.3. Scatterplot showing the association between male and female participants' body fat mass and their thermal resistance R_b 35 min after WBC.

Discussion

The purpose of this study was to investigate a bio heat transfer model for the purpose of thermal resistance analysis. Our results suggest that for both females and males one observes an unsteady behaviour of the body's insulative response. Further, the thermal resistance is time-dependent, and evolves according to a decreasing power law during the rewarming phase. This is most likley due to the unsteady character of the vasodilatation of peripheral tissues during rewarming (fast phenomenon acutely and consequently weakens over time) which persists long after the cooling is stopped, following a deep state of vasoconstriction during the extreme cold (highest values of R_b at $t = 0$).

In addition, a strong difference between males and females was observed despite insulative response to WBC presenting a similar time-evolution trend. Females present a higher thermal resistance than males, which may be due to the differences observed between sexes mean skin temperature (females: 19.61 °C; males: 22.19 °C) immediately after the WBC session [24]. Over time, the ratio in thermal resistance between females and males decreased quasi-linearly to a maximun of a 37% difference corresponding to the thermal resistance at the thermal equilibrium state.

Thirdly, adiposity appears to be a key parameter in the thermal resistance to be taken into account in the definition of appropriate protocols for males and females. However, this results need to be confirmed by further empirical studies incoporating a larger sample sizes.

Limitations of the study

This theoretical study on the role of thermal resistance of the human body in men and women is based on experimental data from measurements in the warming phase. If the results obtained seem relevant and sufficient to draw conclusions on the need to adapt differentiated cryotherapy protocols for men and women, it is nevertheless necessary to complete this study with an analysis of the cooling phase, which is much more complex to apprehend due to technological constraints linked to the use of measuring devices resistant to extreme cold. This is the current limit of the study and a new perspective.

Conclusion

In recent years, there has been an ever-increasing development of structures offering to athletes and trainers whole-body cryotherapy as a complementary therapy for the treatment of sport-related injuries and muscular recovery. Regrettably the protocols used are purely arbitrary and do not meet any scientifically established criteria, especially with no distinction between female and male athlete populations. This study yields an important finding in view of the necessary inclusion of the athletes body thermal resistance which is found to be gender-dependent. Indeed, adiposity of tissues inherent in fat mass percentage appears to be a key parameter in the body thermal resistance to be taken into account in the definition of appropriate protocols for males and females. It appears from this study that immediately after cryotherapy treatment, the average skin temperature in women is 2.6 °C colder than in men. This shows that women are more sensitive to the external thermal environment, especially to extreme cold. This study shows, on the one hand, that the main reason is a higher value of internal thermal resistance in women than in men. On the one hand, the conclusions of this study suggest that in order to achieve the same skin effects on temperature and consequently to cool efficiency tissues in the same way, the duration of cryotherapy protocols should be shorter when considering female compared to male. This assumption will need to be confirmed in future studies.

Conflicts of interest

The authors have no conflict of interest to declare. No financial support was provided for this research.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.mehy.2018.08.017.

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