Combining Infrared Thermography and Computational Fluid Dynamics to Optimize Whole Body Cryotherapy Protocols

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Abstract. Whole Body Cryotherapy (WBC) can be considered a therapeutic complement consisting in placing the human body in a hermetic chamber within which temperature varies between −110 °C and −60 °C over a short period of time. Despite the benefits of cryotherapy, subject safety must be ensured during the exposure to extreme cold, in the sense that the physiology of the human body should not be altered. Thus during a WBC session, accurate knowledge regarding the thermal transfer occurring at the cutaneous surface of the patient is essential. To this end, aeraulic and thermal conditions within the cryotherapy cabin are fundamental. The experimental study presented in this paper is based on the acquisition of skin temperature mappings. The derived boundary conditions are applied to the associated numerical problem which is solved using Computational Fluid Dynamics (CFD).

1 Introduction

WBC first appeared in Eastern Europe and Japan in the 1980s and is a continuation of cultural habits in cold countries. The virtues of a brief complete exposure of the body to intense cold apply to several pathological fields of the musculoskeletal system: rheumatology, traumatology, neurology, muscle recovery [6,13,14,22]. The stimulation of the sympathetic nervous system during the session and the para-sympathetic nervous system immediately after the session will allow for the initiation of a physiological reset, identified as the sources of the benefits of WBC [9,11]. The interest of whole body cryogenic chambers [9] has been demonstrated in the treatment of pain [7,21], inflammation [1,12], joint mobility [10,20], muscle recovery [10,18] and their complementarity with physiotherapy [2,8]. The durations used for the protocols vary from 120 to 240 s, depending on the studies [2,5,19,20]. However, the significance of their influence

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on some results must be underlined. Cryotherapy still suffers from the lack of scientific evidence to validate its techniques and approaches, which are described as empirical. The purpose of this study is therefore to establish a scientific basis for the mathematical modeling of WBC and fill the data void. The implementation of a predictive analytic tool requires a development phase based on the application on a test case of empirically determined evolution laws (temporal evolution of thermal losses). The results, based on iterative calculations composing the estimation tool, will be used to validate the algorithmic process. Finally, the model will be refined and calibrated to build cryotherapy protocols for target populations.

The Physiological Aspect
Body temperature varies following the energy distribution, but also as a consequence of local heat exchange coefficients. Thus, the overall temperature of the central core is about 37 °C while skin temperature at the feet level lies between 29 to 30 °C and 34 to 35 °C (daily variations are observed due to internal and external disturbances [16]). Thus, during a WBC session, skin temperatures decrease sharply to reach local minimum temperatures of around 4 °C [3]. In the human body, two types of thermoregulations can be distinguished. One is a vegetative physiological thermoregulation aimed at maintaining the internal temperature of the body at about 37 °C. The other may be regarded as "behavioral" and provides protection against sudden changes in the environment, in an attempt to lessen the physiological reactions perceived as unpleasant [15].

The Physical Aspect: Heat Exchanges
Continuous heat exchanges between the inner and outer parts of the human body involve a state of equilibrium called homeostasis. Subsequent exchanges between the human body and the environment occur through the skin surface and respiratory tract in the form of sensible and latent heat. Sensible heat is evacuated through the skin surface in three different forms of heat exchanges: convection, conduction and radiation. Besides, latent heat is consumed by sweat evaporation at the skin surface. Given the subject's position in the cryotherapy chamber, it can be reasonably assumed that conductive transfers between the sole of the protective shoes and the cabin floor are negligible.

2 Materials and Methods

Although the study is predominantly theoretical, an experimental contribution is required for the purpose of providing the conditions at the most realistic limits of the problem treated. Infrared thermography, which has already been used in the frame of similar topics, is a non-intrusive analytical method used in medicine to acquire skin temperature mappings at both the microscopic and macroscopic scales [3,4]. All bodies or solids naturally and continuously emit infrared radiations proportional to their temperature: the emitted energy thus depends on the thermal effects (global and/or local surface losses) generated by the cryotherapy session.

Experimental Protocol
A precise calibration was carried out on site, allowing parameter settings adapted to field conditions. To this end, the emissivity of the material to be visualized (the skin) must be set, as well as the reflected apparent temperature of the material and the shooting distance. The camera is placed outside the cryotherapy chamber and controlled via an interface offering extensive configuration of the acquisition parameters, such as number of images or recording duration, temperature range, emissivity or inclusion of measurement points. The subject studied (25 years old, 1,86 m, 75 kg, BFP 9%) followed all the usual guidelines of the standard procedure [3] in WBC session (safety precautions, personal protective equipment, session duration). The resulting thermal images, acquired every 30 s during the session, made it possible to quantify the temporal evolution of heat losses during exposure to extreme cold. These measurements may be carried whether locally or on a whole-body scale, depending on the nature of the desired information. Repeatability of the thermal mappings was validated on the basis of 5 identical experiments, carried out one day apart.

Numerical Protocol for Computational Fluid Dynamics (CFD) Simulation
The numerical simulation of a human being standing in the center of a whole-body cryotherapy chamber and exposed to cold dry air at a temperature of $-110\,^{\circ}\mathrm{C}$ requires a 3D model of the said subject: a 3D scanner was used in this approach. The numerical process also involves selecting relevant physical models, boundary conditions as well as the discretization of the computing domain (i.e. mesh). Our model combines two types of mesh: a surface mesh corresponding to the numerical manikin and a self-adaptive tetrahedral mesh in the vicinity of the subject for the computation of temperature within the cryotherapy chamber. A total of 15 million calculation points at each time step is used to simulate the experimental process. In this problem involving a large temperature difference between the human body and its environment, the surface temperature of the skin and the heat flow around the human body are time-dependent; unsteady computations are mandatory. The numerical solvers also make use of coupled heat transfer modes between radiation (heat radiated from the human body to the cold walls of the chamber) and natural convection (the temperature difference between the skin and the surrounding air generates a variation in air density that will generate a thermal plume). Following these computations, we are able to determine the semi-analytic expression of body heat loss during a cryotherapy session [17]. Once the global and/or local surface losses have been calculated, they are implemented as unsteady thermal boundary conditions applied to the corresponding surface.

3 Results

In this section, the results of the thermal imaging test campaign and CFD computations are presented and compared.

Experimental Results

The infrared thermography images captured every 30 s during the session are depicted in Fig. 1, and aim at bringing better understanding of the thermal phenomena occurring on the skin surface during a WBC session. As a matter of fact, comparing these images enables quantifying the temporal evolution of the skin temperature during a cryotherapy session at $-110\,^{\circ}$C. It is observed that skin temperature undergoes gradual and rapid cooling as more time is spent in the cabin. In addition, the temperature distribution is clearly uneven, with globally higher temperatures in the upper part of the body, neck, chest and upper back, as well as the surroundings of the spine. We can also notice that skin temperature is lower on the thighs and ankles.

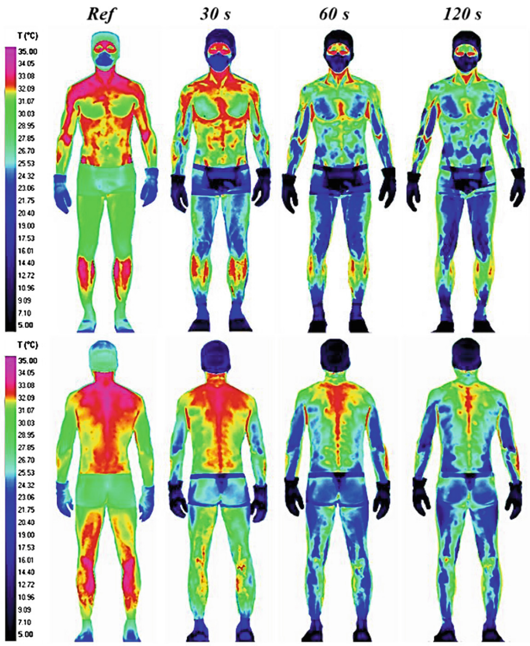

Fig. 1. Infrared thermograms before the session (Ref.), 30 s, 60 s and 120 s after the start of the cryotherapy session at $-110\,^{\circ}$C

Figure 2 summarizes the temperatures averaged on three different areas of the front side of the body. A significant overall temperature drop is observed, with marked differences depending on the area. Thus, the average temperature recorded between the reference measurement and the end of the session (after 3 min) decreases more drastically at the lower limbs (-39%) than at the trunk ($\simeq$32%).

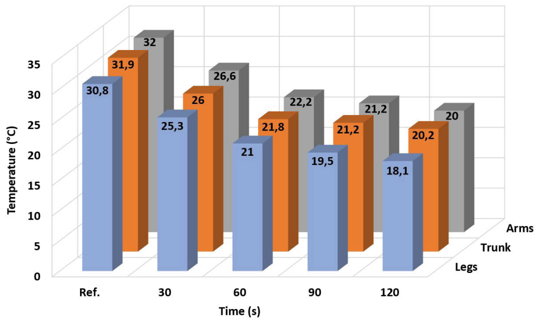

Fig. 2. Average temperature in different areas of the front side of the body, measured every 30 s after entering the cryotherapy cabin

Numerical Results
The accuracy of the theoretical model is assessed by verifying that numerical results supplied by the CFD computation lie within the margin of error of the experimental results, i.e. measurements of the mean skin temperature.

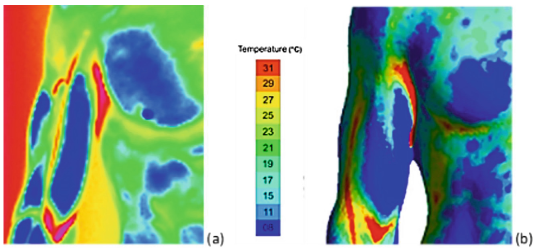

Fig. 3. Comparison in the biceps area between infrared thermogram (a) and numerical simulation (b) after 1 min 30 s of WBC at −110 °C

As seen in Fig. 3, there is good agreement in skin temperature between the numerical model prediction and the experimental thermogram. Similarly, the temperature gradient derived from both procedures is globally of the same order of magnitude.

4 Discussion

From these thermal maps, we were able to extract as much data as possible regarding skin temperature and calculate average values over 6 manually-defined regions of the lower limbs, upper limbs and trunk on the front and back sides of the body (Fig. 4). Ultimately, these values will help determine the zone-wise surface heat flux density, constituting one of the thermal boundary conditions of the problem to be modeled.

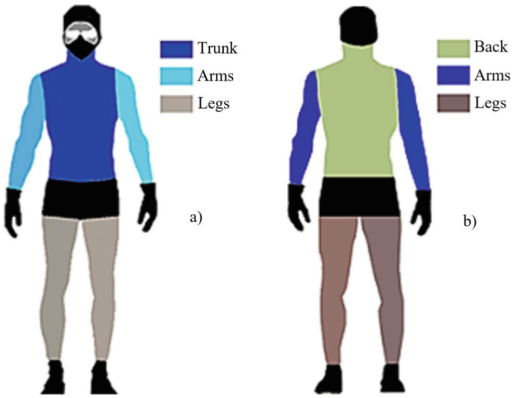

Fig. 4. Partitions of the body used for the calculation of average skin temperatures, on the front (a) and back (b) sides

During the post-treatment of the experimental results, we determined the mean skin temperature over time and compared these data with the results of the numerical simulations (Fig. 5). However, the comparison between the experimental and numerical results indicates that the partitioning of the body surface must be optimized in order to further improve the prediction of skin temperatures. In practice, this will result in a more thorough surface map containing additional areas. Thus, numerical results on the temporal evolution of skin temperatures were compared to data from infrared thermal imaging, demonstrating the predictive potential of the numerical model.

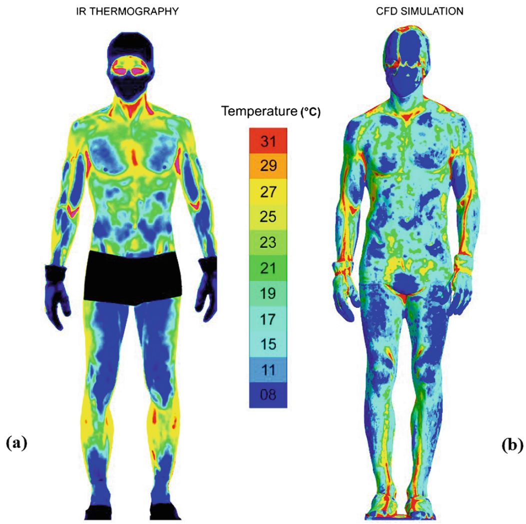

Fig. 5. Comparison between infrared thermogram (a) and temperature mapping computed using CFD code (b) at $t = 90\,s$

5 Conclusions and Prospects

The self-protection mechanisms of the human body are activated in the event of prolonged exposure to extreme temperatures, yet they are not designed to last. Therefore, sound knowledge of the thermal phenomena occurring on the patient's skin surface during a WBC session is fundamental; not to mention that of the aeraulic and thermal conditions within the cryotherapy cabin itself. With this in mind, we conducted this experimental study using infrared and digital thermal imaging along with numerical simulations based on a general-purpose CFD code. The results of infrared thermal imaging provided us with mappings of the patient's skin temperature distribution, as well as their evolution during the cryotherapy session. We were thus able to calculate average temperatures required to determine the surface density of heat fluxes per zone. This thermal parameter is converted into relevant thermal boundary conditions to be implemented in the computation code dealing with convecto-radiative heat transfers. The main advantage of mathematical modeling is that it avoids the multiplication of experiments: modeling could easily be extended to other populations, such as women, sedentary people, etc. The only parameters that would vary would be thermal time constants dependent on the thermal resistance of the human bodies being tested.

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