Series on Biomechanics, Vol.32, No.2 (2018), 12-17

Partial body cryotherapy in confined cryosaunas: effects of inherent thermal stratification

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Abstract

Partial Body Cryotherapy (PBC) is generally used for therapeutic purposes and its positive effects on a wide range of diseases are unquestionable. The efficiency of cryotherapy protocols relies on the perceived intensity of the thermal shock (i.e. the difference between body and ambient temperatures) as well as its duration (between 1 and 3 minutes). This study aims at modelling the thermal transfers between the human body and its environment during a PBC session. A Computational Fluid Dynamics (CFD) method has been applied to investigate all thermo-physical processes involved during a cryotherapy session. Modelling the convective transfers between the human body, the cryogenic fluid and the ambient air allowed highlighting a thermal stratification phenomenon depicted in this article by 2D temperature fields. Results also showed that the temperature throughout the cabin is much higher than the temperature needed. This study proves that a CFD method is suitable for modelling the thermo-physical processes associated with PBC. Developing a numerical framework in this field offers promising prospects in terms of improvements in existing PBC protocols, starting with optimizations of the air/nitrogen mixing processes.

Keywords: Partial Body cryotherapy (PBC), CFD, VOF, nitrogen, thermal stratification

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1. Introduction

Cold has long been used (back to Hippocrates) to cure various diseases. However, it was only in 1979, during the European Rheumatology Congress (Wiesbaden, Germany), that Japanese Prof. Yamauchi introduced the concept of Whole Body Cryotherapy (WBC) to treat inflammatory diseases [1]. In France, this therapy only appeared in 2008 while it was widely used in other countries such as Russia, Poland and Germany [2]. Cryotherapy aims at exposing the subject to temperatures often below -110°C, thus creating a thermal shock responsible for accelerating the expelling of body toxins (recovery) and reducing inflammatory reactions [3-7]. Through thermal body receptors (located in the head mainly), WBC triggers a number of reactions leading to the production of wellness hormones, such as endorphins [8]. Besides, cold induces an analgesic effect (pain relief) by slowing down nerve conduction [9-10]. Cryotherapy sessions therefore reduce fatigue, help relax tight muscles and enhance venous return [11].

Various cryotherapy treatments exist, the most commonly used today being Whole Body Cryotherapy (WBC) and Partial Body Cryotherapy (PBC) [12], the main difference lying in the fact that the patient's head and neck are not treated in PBC. During a PBC session, the subject stands in a cabin encompassing the body up to the shoulders level. The cabin features insulated walls and connections for treatment gas supply and evacuation, the latter being preferably a mixture of dry air and liquid nitrogen from an external cryogenic tank [13]. Liquid nitrogen decompression makes it possible to reach extreme temperatures (down to -190°C) very quickly. Subjects are then exposed for 1 to 3 minutes (based on various criteria), and develop cold struggle mechanisms which in turn produce positive effects on a range of pathologies and traumas [14-17]. A gas evacuation system mounted on the cabin aspirates the nitrogen vapors emitted during device operation. The user stands up still and is immersed up to the shoulders' level. Consequently, the head remains above cold gases and no mouth protection is required. The prescribed temperature is set by the operator and remains constant to a certain extent inside the cabin: the human body actually behaves like a heat source and alters the distribution of temperature. Besides, it is worth noting that the temperature measurement point is located near the nitrogen inlet, where temperatures are the lowest [18]. Thus, the temperature displayed on the monitoring screen is likely to vary from that inside the cabin.

The success and efficiency of a cryotherapy protocol mostly lie in the intensity of the "thermal shock" experienced by the patient [9, 19]. Two main parameters are involved: the duration of the protocol (usually between 1 and 3 minutes) and the temperature inside the cabin. A significant lack of data related to the actual temperatures inside the cabin (PBC) or chamber (WBC) during treatment may partially account for the discrepancies between exposure protocols described in the scientific literature [12]. Experimental studies so far essentially investigated the effects of cryotherapy treatments on skin and body temperature of the patient [11, 19-23]. To the authors' knowledge, the only study dedicated to the evolution of temperature inside a PBC cabin was carried out by Savic *et al.* [18]. The extreme temperatures involved require displacing the measurement devices and using dedicated sensors [24]. Thus, numerical tools constitute an interesting alternative to experimentation, not to mention that they provide data which would be hard to gather via *in situ* measurements [25]. The study described herein examines the use of a CFD (Computational Fluid Dynamics) method to analyze the thermo-physical processes associated with PBC for therapeutic purposes. The main objective is to determine the temperature cartography and stratification in a PBC cabin through 2D numerical simulations. Results are compared to experimental data collected by infrared thermography. Simulations were performed for a duration equivalent to a 3-minute cryotherapy session.

2. Methods

In a first step, a CAD model of the cabin was created, including the nitrogen inlets and outlets. In order to reduce the computational time, we used the axis symmetric formulation. In this case, only half of the geometry and calculation domain was drawn. It is worth noting that the 2D geometry of the PBC cabin used in the whole study has dimensional features equivalent to those of the commercial models. In a second step, a man's profile (approx. 1.9 m) was placed in a standing position at the center of the cabin. The cabin is then virtually placed inside a calculational domain (Fig.1) to model the convective exchanges between the cryogenic fluid and the ambient air. The working principle of a "Cryo-sauna" PBC cabin relies on the mixing of liquid nitrogen and dry air to cool down the inside volume of a treatment space (Fig. 1a). In an attempt to reproduce the working principle with maximal accuracy, the nitrogen is mixed with dry air and injected into the cabin with an average mass flow of 3 kg/min at a temperature of 83 K [13]. In order to accurately model the heat exchange between human body and its environment, a heat flux of $85 w.m^{-2}$ was applied as a thermal boundary condition to the human body [26].

Table 1
Boundary conditions

Mass flow Inlet (Nitrogen/air mixture)	***Mass flow rate = 0.05 kg.s^{-1}, T = 83 K***
Pressure outlet top (Nitrogen/air mixture)	P = -10 Pa
Pressure outlet (Air)	P = 1 Atm
Wall Boundary (calculation domain)	Q = 0 W.m^{-2} , adiabatic surfaces, ε = 1
Wall Boundary (cryotherapy cabin)	Q = 0 W.m^{-2}, adiabatic surfaces, ε = 1
Wall Boundary (Heated body)	Q = 85 W.m^{-2}, ε = 0.98

In addition, a radiation model is used to accurately model the interaction between the heated body and its environment. Boundary conditions are summarized in Table 1. A vacuum condition is applied at the outlet nozzle placed at the top of the cabin, allowing suction of nitrogen vapors before they reach the patient's head (Fig. 1, Table 1).

During initialization of the computation, temperature in the calculation domain is set at an ambient level of 293 K. The iterative computation subsequently determines the evolution of temperature in the cabin at each time step.

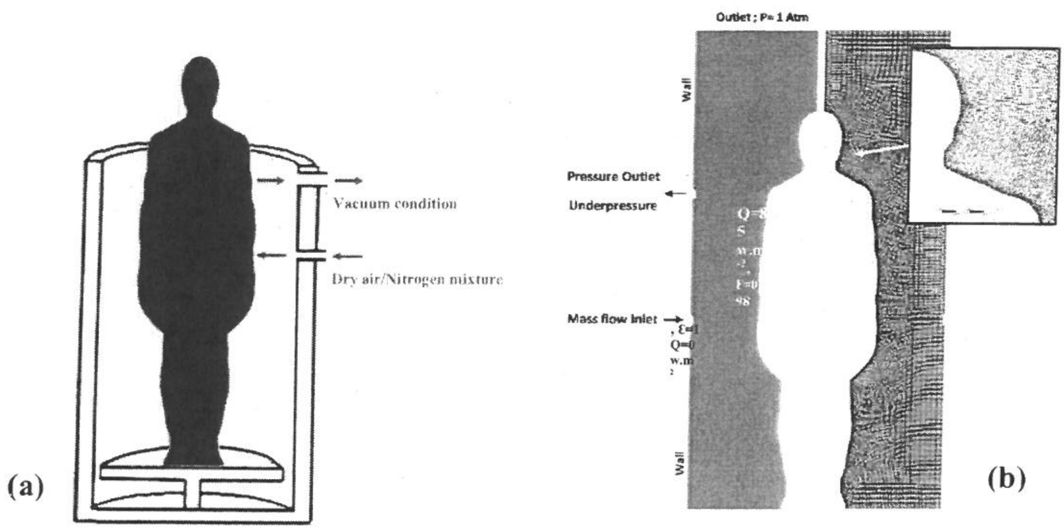

Fig. 1. The cold source in the cryotherapy cabin is the injection of a mixture of dry air and liquid nitrogen in the cryotherapy cabin (a); Calculation domain, boundary conditions on the left and domain mesh on the right (b).

During system operation, cabin cooling is achieved through mixing of dry air and liquid nitrogen. Nitrogen is a material which shifts phases (liquid or gas) depending on the temperature: its physicochemical characteristics are therefore strongly thermally dependent. The density of dry air and Nitrogen can be calculated using the ideal gas law, expressed as a function of temperature and pressure.
In this 2D study, we used the axis symmetric formulation for the purposes of reducing computational time. In this case, only half of the calculational domain was modeled and symmetry conditions were applied.

2.1. Numerical model

The calculational domain was meshed using the software ANSYS Workbench Meshing®. The two-dimensional mesh that we used in this study consists of hexahedral and tetrahedral cells. The unstructured mesh is refined near the body surface where a high resolution of the boundary layer is necessary and coarser in the far field.

In our study, the problem to be solved is two-dimensional, time-dependent and not isothermal. Because of the temperature difference between the human body (about 304 K) and the surrounding fluid (stagnant air at 83 K), the flow near the body is considered a natural convection flow [27]. Heat transfer phenomena occurring between the human body and its environment (convection, radiation) are simulated using the S2S (Surface to Surface) model. Moreover, the energy equation was enabled. The thermal boundary layer and the airflow around the human body are considered to be totally turbulent. In this study, the k-Ɛ turbulence model was chosen for the closure of the Reynolds Navier-Stokes average equations.

General-purpose commercial code ANSYS Fluent 18.0® was used to compute the two-dimensional flow in the calculation domain with the mixture multiphase model. Compared with the multiphase model of others, the mixture model allows the phases to be interpenetrating and to move at different velocities, using the concept of slip velocities. Moreover, there is interaction of the inter-phase mass, momentum and energy transfer [28]. The SIMPLE algorithm was preferred to solve the pressure-velocity coupling, using a first-order discretization scheme. An adaptive time-step ensures faster convergence of the results.

3. Results and discussion

Fig. 2 shows the thermal stratification profiles for 20s, 80s, 140s and 180s after the beginning of the cryotherapy session. These are plotted along the vertical axis (horizontal distance to the cabin wall y=0.4

m, Fig. 3a). We can clearly see that the temperature decreases over time to t=140s. From this moment on, we can see that the temperature is globally homogeneous in an area located between the bottom of the cabin up to a height of 0.9m, which corresponds approximately to the level of the patient's trunk. Above 0.9 m, the temperature gradually increases to the level of the extraction nozzle located at the patient's shoulder. It should be noted that the heat gain due to the human body causes an overall rise in temperature inside the cabin with a rapid increase in temperatures for heights between 90 and 160 cm. The gas mixture at the bottom of the cabin maintains a temperature close to that of the injected air/nitrogen mixture, while in the upper part of the cabin, the mixture is influenced by the air at ambient temperature. Consequently, a temperature gradient occurs in the vertical direction.

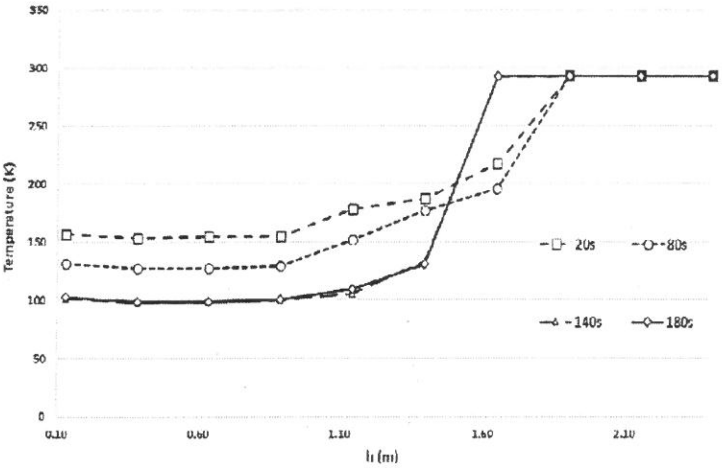

Fig. 2. Temperature profiles plotted along the vertical axis (horizontal distance to cabin wall y=0.4 m) for 20s, 80s, 140s and 180s following the beginning of the cryotherapy session.

Fig. 3 a) shows the temperature fields of the nitrogen/air mixture inside the cryotherapy cabin at t = 3 min. Cryogenic cabin manufacturers generally provide real-time information on the temperature inside the cabin. The temperature displayed on the cabin control panel is measured at the nozzles (point where nitrogen is being injected) and does not necessarily reflect the actual temperature inside the cabin [18]. The results in Figure 3 show that the temperature throughout the cabin is significantly higher than the temperature of the cryogenic fluid injected at 83K and shows substantial heterogeneity in the temperature distribution. The thermal stratification appears noteworthy ($\Delta t<104K$), as well as the minimum and maximum temperatures. Fig. 3b shows a picture taken with a digital infrared camera of a patient which has just finished a 3-minute session. The corresponding methodology is detailed in a previous article [29]. This thermogram clearly shows aheterogeneity in the distribution of skin temperatures. We can clearly see that the cooling is more pronounced in the lower body (legs). The data in this thermogram is to be correlated with our numerical results. The heterogeneity of skin temperatures is undoubtedly due to the thermal stratification found in the cabin. In addition, a boundary layer forms along the body (Fig. 3a), as a consequence of heat transfer between the human body and its close vicinity.

4. Limitation of the study

In recent years, there has been an ever-increasing development of structures offering whole or/and partial body cryotherapy as a complementary therapy in sports and medicine. Paradoxically, it appears in the literature that adequate protocols on thermal shock duration as well as temperature threshold to be attained are purely arbitrary and do not meet any scientifically established criteria. Although this preliminary study is 2D, which may be a scientific limitation, it nevertheless shows that the idea that temperatures are homogeneous within cabins is incorrect and that strong thermal gradients are present. Taking into account that the three-dimensional character will be an extension of this study, with the aim of optimizing the nozzles (location, flow rates…) for the supply and extraction of refrigerant gas in order to make the internal temperature of the cabin homogeneous .

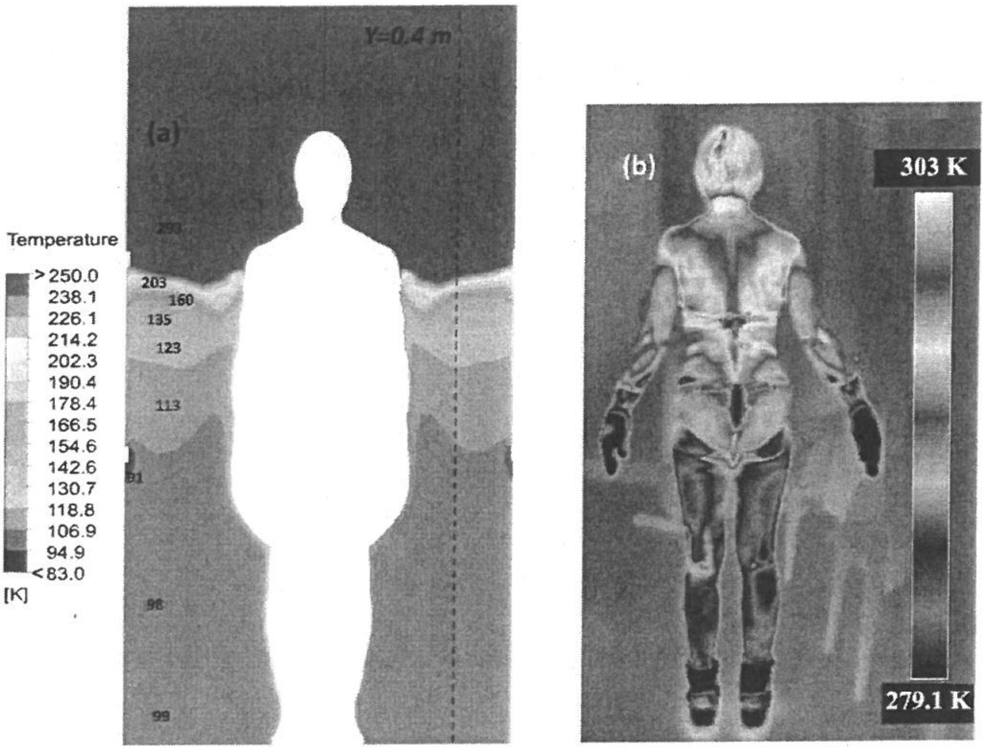

Fig. 3. (a) Temperatures inside the cabin, range was limited to the 83-250 K interval for the sake of visibility of the temperature gradient; simulations performed for a time frame equivalent to 3 minutes of treatment. (b) Thermogram obtained after 3 min treatment in PBC cabin at -140 °C, captured by infrared thermography (thermal camera FLIR SC620).

5. Conclusion

The knowledge of temperature distribution inside a Partial Body Cryotherapy (PBC) cabin provides useful insight into the improvement of treatment protocols (duration, temperature). In this context, we carried out a numerical 2D study using the CFD method. A turbulent mixture model was employed to study the processes involved in the mixing of air and nitrogen, both exhibiting thermally dependent behavior. We have highlighted a significant heterogeneity of temperatures within the cabin. Our results also showed that the average temperature is much higher than the temperature needed. This is important because a precise knowledge of the temperature inside the cabin is necessary in order to adapt cryotherapy protocols to specific patients' requirements. Moreover, infrared thermal imaging has been applied on a patient after a 3-minute session of Partial Body Cryotherapy (PBC). The resulting picture was compared to a CFD analysis temperature field, and clearly demonstrated a good correlation between thermal stratification and temperature distribution on the patient's skin.
Finally, the CFD method proves to be perfectly suitable for modeling convective exchanges between the human body, the cryogenic fluid and the ambient air. In the continuity of the work undertaken in this study, a 3D modeling would provide a better sensitivity of the temperature distribution during cryotherapy sessions of 3 minutes. Relying on numerical results and medical support, it would be possible to optimize treatment protocols in order to obtain better results on patients.

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