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Validation of a new whole-body cryotherapy chamber based on forced convection

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ABSTRACT

Whole-body cryotherapy (WBC) and partial-body cryotherapy (PBC) are two methods of cold exposure (from −110 to −195 °C according to the manufacturers). However, temperature measurement in the cold chamber during a PBC exposure revealed temperatures ranging from −25 to −50 °C next to the skin of the subjects (using isolating layer placed between the sensor and the skin). This discrepancy is due to the human body heat transfer. Moreover, on the surface of the body, an air layer called the boundary layer is created during the exposure and limits heat transfer from the body to the cabin air. Incorporating forced convection in a chamber with a participant inside could reduce this boundary layer. The aim of this study was to explore the use of a new WBC technology based on forced convection (frontal unilateral wind) through the measurement of skin temperature. Fifteen individuals performed a 3-min WBC exposure at −40 °C with an average wind speed of 2.3 m s^{-1}. The subjects wore a headband, a surgical mask, underwear, gloves and slippers. The skin temperature of the participants was measured with a thermal camera just before exposure, just after exposure and at 1, 3, 5, 10, 15 and 20 min after exposure. Mean skin temperature significantly dropped by 11 °C just after exposure ($p < 0.001$) and then significantly increased during the 20-min post exposure period ($p < 0.001$). No critically low skin temperature was observed at the end of the cold exposure. This decrease was greater than the mean decreases in all the cryosauna devices with reported exposures between −140 °C and −160 °C and those in two other WBC devices with reported exposures between −60 °C and −110 °C. The use of this new technology provides the ability to reach decreases in skin temperature similar to other technologies. The new chamber is suitable and relevant for use as a WBC device.

1. Introduction

Whole-body cryotherapy (WBC) and partial-body cryotherapy (PBC) are two methods that consist of exposing one to several subjects to extremely cold dry air for a period of one to four minutes. It has been reported that cold applications provide physiological, psychological and physical benefits (Bouzigon et al., 2016; Dugue, 2015). These methods have been developed to improve exercise recovery and relieve pain, depression and anxiety symptoms in patients suffering from rheumatism and inflammatory diseases (Bouzigon et al., 2016).

Currently, there are two types of technology for these treatments. Whole-body cryotherapy requires a cryogenic chamber in which the individual is entirely exposed to cold, and PBC consists of an open cabin in which the individual is exposed to cold, excluding the head and neck. For both treatments, individuals wear minimal clothing (a bathing suit, cap, gloves, socks, slippers and a surgical facemask for the WBC). These two types of technology require the use of nitrogen to create extremely cold temperatures (Bouzigon et al., 2016). At present, there is a lack of information in the literature concerning WBC and PBC, especially regarding the actual temperature of exposure inside the chamber or cabin. Only one study has presented the actual temperature in a PBC device (Criomed, Kherson, Ukraine) during an exposure

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(Savic et al., 2013). The authors reported temperatures of approximately −25 °C with a participant inside the cabin and −50 °C in the centre of the cabin without a participant inside. These data are important as they indicate a difference in the temperature of exposure produced by the PBC device (from −140 °C to −195 °C) and the actual temperature. No data are available concerning the temperatures inside WBC chambers. The temperature provided by the WBC device is −110 °C, but no data have been presented in published studies.

The discrepancy between temperatures provided by devices and actual temperatures during exposure may be due to the position of thermal sensors. In PBC, temperatures are measured at the outlet of nitrogen nozzles (Bouzigon et al., 2016). Due to the properties of nitrogen, the temperature of sprayed nitrogen can range from −110 °C to −195 °C but may differ from the actual temperature in the centre of the cabin. Moreover, when a subject is inside the cabin, the temperature increases (Savic et al., 2013) due to the heat transfer from the body through radiation, conduction and natural convection mechanisms.

However, on the surface of the human body, an air layer called the boundary layer is created during the exposure and limits heat transfer from the body to the cabin air (Schlichting, 1968). Human body convection and the boundary layer are thus important to consider in the efficiency of WBC and PBC devices when cooling air, especially in small compartments such as a PBC cabin. Nevertheless, incorporating a forced convection (wind chill) in a chamber with a participant inside could reduce the boundary layer phenomenon (Osczevski and Bluestein, 2005). By definition, wind chill is a three- or four-digit number representing the rate of heat loss of a plastic bottle per unit of area (Siple and Passel, 1999). This index has been improved through several studies (Osczevski and Bluestein, 2005; Osczevski, 1995) and has been transformed into wind chill equivalent temperature (WCET in degrees Celsius and Fahrenheit). The WCET provides the perceived temperature in a chamber according to the wind speed in front of an individual.

The efficiency of WBC and PBC devices is traditionally assessed by measuring the variation in an individual's skin temperature before and after exposure (Bouzigon et al., 2016; Hausswirth et al., 2013; Savic et al., 2013). Indeed, the interaction between the human body and the cryocabin or cryochamber occurs principally at the skin level, and skin temperature may reflect the balance between heat loss to the environment and heat produced by metabolically active tissues (Cholewka et al., 2006). However, due to the short duration of exposure the extreme cold could lead to a vasoconstrictive effect, which increases insulation and reduces heat exchange (Stocks et al., 2004). During a cold exposure, the body's thermoregulatory system attempts to maintain a constant core temperature (37.0 ± 0.8 °C) through vasoconstriction mechanism and an increase in metabolism (shivering). Short exposures lead to a small decrease in core temperature (Costello et al., 2012), but the skin temperature drops immediately. The strong variations in skin temperature induced by exposure to extreme cold lead to stimulation of cutaneous thermoreceptors and, therefore, the thermoregulation centre in the hypothalamus. The sympathetic adrenergic fibres become excited, causing local arterioles and venules to constrict and thereby reducing nervous conduction velocity (Herrera et al., 2010). Moreover, the decrease in blood flow reduces local metabolic processes, consequently attenuating inflammatory symptoms and the formation of oedema around injured tissues (Paddon-Jones and Quigley, 1997), which can occur after physical exercise or in some pathologies.

To date, no data are available concerning the use of WBC with a forced convection system for human skin temperature changes during cold exposure.

The aim of this study was to establish the validation of a new WBC technology based on forced convection by measuring the decrease in skin temperature during a 3-min exposure set at −40 °C. We hypothesized that the decrease in skin temperature in the chamber would be similar to those measured in other existing classical chambers and cabins.

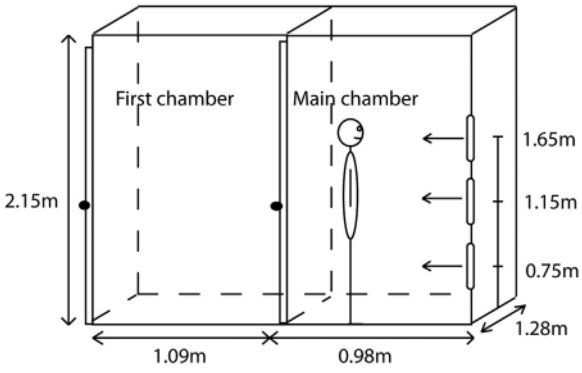

Fig. 1. Cold chamber drawing showing the position of the three fans in the main chamber. The wind velocities at 1.65, 1.15, 0.75 m were at 3.7, 1.9, 1.5 m s^{-1}, respectively.

2. Material and methods

2.1. Study design

This study was conducted to assess the effects of a WBC technology based on WCET (Cryantal Development, Noisiel, France) on skin temperature and temperature measured in the ear canal. This WBC device (Fig. 1) comprised two chambers. The first chamber was used to habituate the individual to cold dry air and to isolate the second chamber. The second chamber was the main exposure compartment. In this chamber, three fans combined with the cold temperature, allowed even colder conditions.

Skin and ear temperatures were assessed before, immediately after and within 20 min after exposure. The temperature of exposure was measured when the chambers were empty and when participants were inside. The study took place in a fitted trailer that contained a mobile WBC. The mean temperature inside the trailer during the investigation was 21.0 ± 1.6 °C, and the mean hygrometry was 51.7 ± 8.9%.

2.2. Participants

Fifteen healthy volunteers (10 males and 5 females) participated in this study. Their characteristics are presented in Table 1. Body fat percentage was assessed using the sum of skinfold measures (biceps, triceps, subscapular and supra-iliac) with a Harpenden skinfold calliper. All of the participants volunteered and signed a statement of informed consent at their enrolment. All of the participants performed WBC regularly, and this study did not expose them to unknown extreme conditions. The study, whose protocol was accepted by the local medical commission, was conducted in a medical centre (Noisiel, France) and in accordance with the Declaration of Helsinki (2001).

2.3. Exposure protocol

First, volunteers were exposed 30 s at −20 °C in the first chamber and then 3 min at −40 °C in the main chamber. During the exposure, volunteers wore a headband over their ears, a surgical mask, underwear, gloves, socks and slippers. Men wore briefs and women panties and bras. Inside the chamber, they were required to stand still in front of the fans. At the end of the exposure, they exited the chamber within 10 s and were instructed not to rub their skin. They removed their mask, gloves and headband and situated themselves in the same position as before the exposure when their prior thermal measurement was taken.

2.4. Measurements

2.4.1. Chamber temperature

Before the experiments, the temperatures inside of the two empty

Table 1
Subject characteristics.

	Age (years)	Height (cm)	Weight (kg)	Body fat (%)	BMI (kg.m m^{-2})
Subjects (n=15)	38.7 ± 8.2	174.6 ± 8.0	70.8 ± 10.0	20.1 ± 8.4	23.1 ± 2.3
Males (n=10)	38.6 ± 9.8	179.0 ± 4.2	74.9 ± 8.1	15.5 ± 5.0	23.3 ± 2.0
Females (n=5)	39.0 ± 4.5	165.8 ± 6.5	62.6 ± 8.6	29.5 ± 5.4	22.8 ± 3.1

chambers were controlled with five T type thermocouples (TC Direct, Dardilly, France). The sensitivity of these thermocouples was ± 0.05 °C. The thermocouples were fixed on a tripod at heights of 20, 55, 90, 125 and 160 cm and used when the cold chamber was empty. However, due to the tripod's large size, only one thermocouple (90 cm high) per chamber was used during each participant exposure. The size of the first chamber was is 1.09×1.28×2.15 m and the size of the main chamber was 0.98×1.28×2.15 m (Fig. 1).

In the main chamber, the WCET was calculated using the equation by Osczevski and Bluestein (2005):

$$\mathbf{WCET}\ (°C) = \mathbf{13.12} + \mathbf{0}.6215T - \mathbf{11.37S^{0.16}} + \mathbf{0.3965TS^{0.16}}$$

T is the temperature (°C) and S is the wind speed (km h^{-1}). The wind speed must be multiplied by 1.5 due to the distance in front of the individual (Osczevski and Bluestein, 2005) and was measured with a Kestrel 4250 anemometer at 60 cm from the fans (Kestrel, Birmingham, United Kingdom).

2.4.2. Skin temperature

Skin temperature was measured before, immediately after (post, 10 s) and within 20 min after the exposure with a VarioCAM® h head thermal camera (Jenoptik, Jena, Germany) and connected to the IRBIS3® Infratec software.

The infrared thermal camera is a non-invasive tool for measuring temperature and provides the surface temperature of a body. Thermal imaging was considered a safe and suitable method for monitoring skin temperature during and after a cryotherapy treatment at both clinical and sports levels (Matos et al., 2015). On the camera, we installed a type 1 lens with a focal length of 50 mm (Infratec, Infrared). The range of temperature measurement of the VarioCAM® h was between −40 °C and 1200 °C with an accuracy of ± 2% in the measurement range. The radiometric thermographic system was based on an uncooled microbolometer FPA detector at 640×480 IR pixels. The camera spectral range was between 7.5 and 14 µm.

Participants were instructed to stand still in the same posture before and after the exposure. They were instructed to stand in front of the thermal camera with palms open and head straight. Thermal captures were performed before the exposure, 10 s after the exposure and 1, 3, 5, 10, 15 and 20 min after the exposure.

The emissivity of the body was set within a range of 0.97–0.98 (Villasenor-Mora et al., 2009). The camera was mounted on a tripod and positioned in a corner of the trailer. The distance between the camera and the participants was 1.60 m. The size of the trailer did not allow a greater distance and consequently did not provide an entire body view. The measurement zone was between the forehead and the upper thighs. The zones of interest were the forehead, right and left chest, arms, forearms, abdomen, upper thighs and palms (Fig. 2). The mean skin temperatures corresponded to the mean values calculated of the forehead, chest, arms, abdomen and upper thighs. The temperatures of the palms were removed because of the poor quality of the captures of these zones in several participants.

2.4.3. Ear canal temperature

The temperature measured in the ear canal was assessed before the exposure and 3, 10 and 20 min after the exposure with an infrared Thermoscan tympanic thermometer (Braun, Kronberg, Germany) (Nimah et al., 2006).

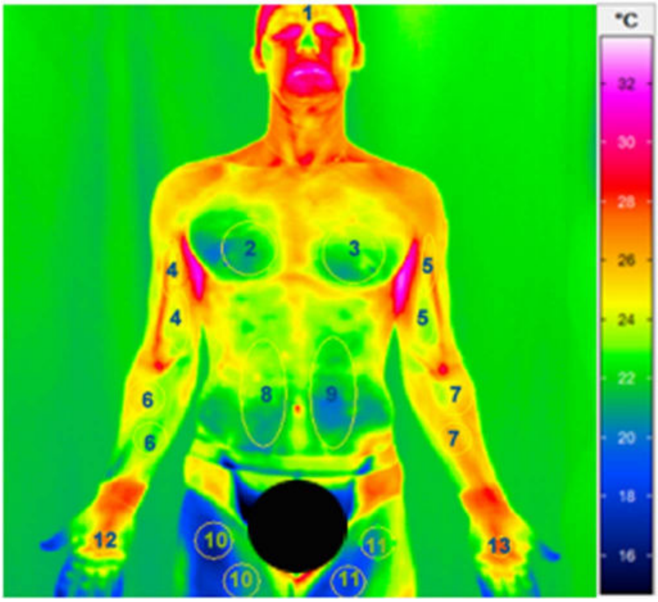

Fig. 2. Measurement zones.

2.4.4. Thermal sensations

The rate of perceived temperature and thermal sensations during WBC were recorded after the exposure using perceptual scales. Perceived temperature was assessed with a nine-point scale “4 – Very hot, 3 – Hot, 2 – Warm, 1 – Slightly warm, 0 – Neutral, −1 – Slightly cool, −2 – Cool, −3 – Cold, −4 – Very cold” (Smolander et al., 2004). This scale is the same as used in ISO 10551. Thermal sensation was assessed with a thermal sensation scale graduated from “0 – Excellent” to “10 – Unbearable” (Lundgren et al., 2014). After the exposure, participants were asked the question, “On average, how did you feel during the exposure?”.

2.5. Statistical analysis

The statistical program used was SigmaPlot 12.0 Software (Systat Inc., San Jose, CA, USA). The results were expressed as the mean and standard deviation (SD). We tested the normality of each variable using the Shapiro-Wilk test. Skin temperature and cardiovascular data were logarithmically transformed to reduce non-uniformities of their distribution when they were not normally distributed (Hopkins et al., 2009). The analysis of the differences in skin temperature before and after the exposure were performed with the Mann-Whitney test. Furthermore, a 95% confidence interval (CI) for between-condition differences was estimated, and a Cohen's *d* effect size (ES) analysis was performed to determine the magnitude of the effect of WBC on skin temperature. According to Cohen (Cohen, 1990), effect sizes of < 0.20 are classified as trivial, 0.20–0.49 are small, 0.50–0.79 are moderate, and > 0.80 are large effects. An analysis of variance (ANOVA) with repeated measures was used to determine the significant mean effects for changes over time after exposure. A post hoc comparison was performed with the Holm-Sidak multiple comparisons test. Test-retest reliability of the skin temperature measurement was assessed using change in mean skin temperature, typical error, and Pearson's correla-

Table 2
Temperature at different heights inside the empty cold chambers.

Thermocouple position (cm)	First chamber temperature (°C)	Main chamber temperature (°C)	Main chamber WCET (°C)
160	−20.3	−32.9	−46.7
125	−19.8	−33.0	−42.8
90	−20.2	−32.1	−41.7
55	−20.5	−31.8	−40.2
20	−20.7	−31.9	−40.4
Coefficient of variation	1.7%	1.8%	6.2%

Abbreviation: WCET=Wind Chill Equivalent Temperature.

tion, as proposed by Hopkins (Hopkins, 2000). Two 3-min exposures with an average of 3 days in-between were performed in 12 participants, and the variations in mean skin temperature before and immediately after the exposures were compared.

3. Results

3.1. Chamber air velocity and temperature

The wind speed measured inside the empty main chamber was 3.7 m s^{-1} in front of the upper fan, 1.9 m s^{-1} in front of the middle fan and 1.5 m s^{-1} in front of the lower fan. The actual temperatures inside the empty chambers are presented in Table 2. The mean temperatures of exposure measured inside the two chambers during the exposures of the subjects were −13.4 ± 2.1 °C in the first chamber and −34.5 ± 3.0 °C (WCET) in the main chamber.

3.2. Skin temperature

3.2.1. Thermal imaging measures reproducibility

A significant correlation (r=0.75; $p < 0.001$), a nonsignificant change in means (p=0.92; Confidence interval (95%): −0.87/1.38) and typical error of 0.08 °C and 0.14 °C indicated good reproducibility of the skin temperature measurements with the thermal camera.

3.2.2. Difference in skin temperature before and after the exposure

Skin temperature decreased significantly for all of the zones of interest ($p < 0.001$). All of the effect sizes were large (Table 3). The most important effect size was reported for the skin temperature decrease of the upper thighs. The mean decrease in skin temperature for the whole body was −11 °C.

3.2.3. Change in skin temperature within 20 min after exposure

The skin temperature for each zone of interest significantly increased within the 20 min after the exposure when compared with the temperature observed just after the cold exposure ($p < 0.001$) (Fig. 3). The skin temperature of the arms increased significantly within 3 min ($p < 0.001$); the forehead and chest skin temperatures increased significantly within 10 min ($p < 0.001$); and the abdomen, upper thighs and mean skin temperature increased significantly within 15 min ($p < 0.001$).

Table 3
Skin temperatures before and immediately after a 3-min cold exposure (Mean ± SD), effect size (ES) and confidence interval (CI: 95%) in fifteen participants.

Zones of interest	Before	After	Effect size (CI 95%)
Forehead	33.5 ± 1.1	24.0 ± 1.9	6.2 (5.6–6.7)
Chest	32.5 ± 1.4	22.6 ± 2.1	5.7 (5.1–6.3)
Arms	32.5 ± 0.9	22.5 ± 3.0	4.8 (4.0–5.5)
Abdomen	32.0 ± 1.5	20.3 ± 2.2	6.3 (5.6–7.0)
Upper thighs	30.6 ± 1.5	17.0 ± 1.8	8.7 (8.1–9.2)
Mean skin temperature	32.2 ± 1.0	21.2 ± 1.7	8.3 (7.8–8.8)

Results are expressed as their mean and standard deviation in 15 subjects.

After the exposure, the forehead skin temperature was the only one to recover its baseline value. In fact, there was no significant difference between forehead skin temperature before the exposure and 10 min after the exposure.

3.3. Ear canal temperature

The ear canal temperature did not decrease after a 3-min exposure. The mean ear canal temperature before the exposure was 36.1 ± 0.6 °C, and it was 35.8 ± 0.6 °C for three and five minutes after the exposure and 36.1 ± 0.5 °C ten minutes after the exposure.

3.4. Thermal sensations

The mean perceived temperature during a 3-min exposure was −3.0 ± 0.8, corresponding to “cold”, and the score for thermal sensations was 6.0 ± 1.9, corresponding to “not very good” sensations.

4. Discussion

The aim of this study was to establish the first validation of a new WBC technology based on forced convection through the measurement of skin temperature.

The first important finding of this study was the marked decrease in skin temperature with this new technology. The mean skin temperature dropped by 11 °C after a 3-min exposure. This finding was consistent with those reported in previous studies using other cold-producing technologies. This decrease was greater than the mean decreases in all of the cryosauna devices with reported 3-min exposures between −140 °C to −160 °C. It was also greater than the decrease in the WBC Zimmer for a 3-min exposure at −60 °C. Additionally, it was greater than the decrease in an unknown model of WBC chamber used by Cholewka et al. (Cholewka et al., 2012) for a 3-min exposure at −110 °C. The only studies that reported a greater decrease in mean skin temperature for the whole body with 3-min exposures at −110 °C and −135 °C were those of Hausswirth et al., and Selfe et al. (Hausswirth et al., 2013; Selfe et al., 2014) (Table 4). In the literature, the decrease in mean skin temperature with a 3-min PBC exposure varied from −7.6 to −9.7 °C (Fonda et al., 2014; Hausswirth et al., 2013; Louis et al., 2015; Savic et al., 2013) and varied from −4.9 to −14.8 °C with a 3-min WBC exposure (Cholewka et al., 2012; Hausswirth et al., 2013; Selfe et al., 2014). Table 4 summarizes the changes in skin temperature produced using our new techniques as well as the changes observed previously using other technologies. The decrease in skin temperature per zone indicated that the wind chill WBC technology was more efficient than the PBC and WBC chambers (unknown model) used in the study by Cholewka et al. (Cholewka et al., 2012). In relation to the forehead, the skin temperature decrease after exposure with wind chill WBC technology was greater than the decrease after the exposure in PBC Krion (Krion, Saint Petersburg, Russia) and the decrease after the exposure in an unknown WBC model used in the Cholewka study (Cholewka et al., 2012; Louis et al., 2015). Our results related to the forehead temperature decrease are interesting because it has been demonstrated that skin temperature decreases in the face accentuate the benefits of WBC in the sympathetic nervous system (Hausswirth et al., 2013). The authors hypothesized that a higher magnitude of the baroreflex would concomitantly occur with the activation of the trigemino-cardiac reflex receptors when the face was exposed to cold. For the other zones of interest, the wind chill WBC technology remained slightly less effective than existing WBC chambers.

Interestingly, we observed that even if the colder temperature of exposure in the WBC Cryantal was measured at the top of the room, the most important variation in skin temperature was measured at the level of the upper thighs (Tables 3 and 4). This was probably because the most

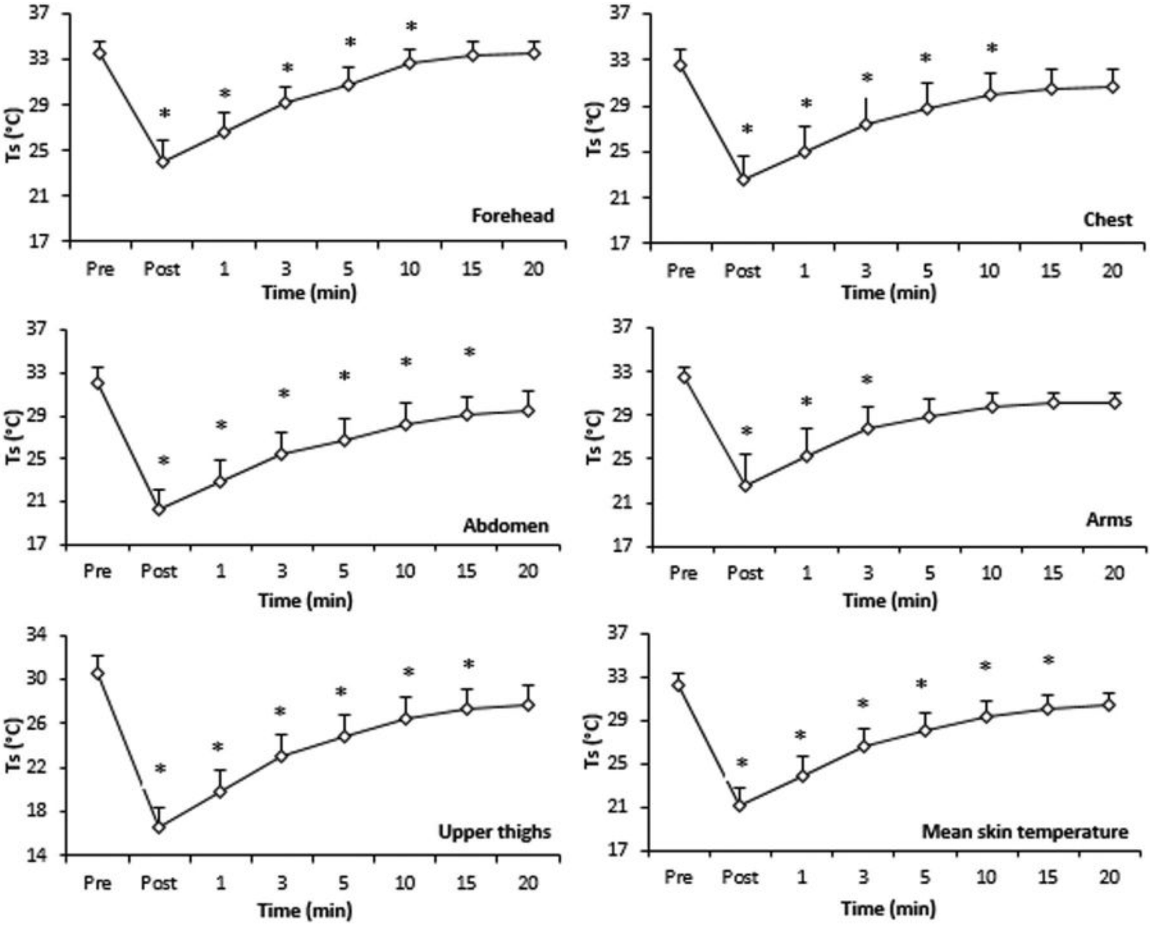

Fig. 3. Skin temperature before, just after and during 20 min after a 3-min WBC exposure in fifteen participants (*: significant difference from the previous measurement). Abbreviation: Ts: skin temperature.

important fat layer is in this area of the body. Fat is an insulator, and it is more difficult to decrease the temperature of a thick fat layer (Hammond et al., 2014). However, once cooled, the fat layer warms up more slowly. Thus, the colder skin temperatures measured at the level of the upper thighs may have been due to the cooled fat layer in this area.

Even if the temperature was colder at the top of the main chamber, the coefficient of variation between the temperatures of the top and bottom of the chambers was low, indicating strong homogeneity of the temperature.

After the exposure, the forehead skin temperature was the only one to recover its baseline value, and it did so in a short time (post 10 min). It is interesting to note that the forehead temperature had the smallest decrease during the exposure and quickly returned to the baseline temperature after the exposure. However, the temperatures of other zones of interest did not return to baseline values within 20 min after the exposure. These findings were consistent with those reported in other studies (Fonda et al., 2014; Hausswirth et al., 2013; Savic et al., 2013; Selfe et al., 2014; Westerlund et al., 2003). However, Zalewski et al. (2013) showed higher skin temperatures than baseline values 3 h after exposure.

Interestingly, the wind chill WBC technology appeared to be suitable for decreasing skin temperature. This could be explained by the ability of wind to extract heat from the body. Air has a poor heat transfer coefficient, but if wind is added, the heat transfer is increased by forced convection (Osczevski and Bluestein, 2005). This technology based on WCET allows for decreases in skin temperature to be reached that are similar to those of other technologies while the actual temperature of the exposure is less cold. A 3-min exposure at −40 °C with wind chill WBC technology appeared suitable to induce a skin temperature decrease. This finding was interesting because it demonstrated the efficiency of a new technology to decrease skin temperature without having to produce a temperature of −110 °C inside the chamber.

The second interesting finding of this study was the small difference in temperature between an empty chamber and a chamber with a participant inside. It has been shown that an empty PBC can reach −110 °C, but with a participant inside, the temperature of exposure is approximately −25 °C (Savic et al., 2013). The authors hypothesized that the air temperature in a PBC with a participant inside is less cold due to the heat transfer from the participant's body to the cabin. The difference in temperatures observed in this study between an empty chamber and a chamber with a participant inside was less important than the difference observed in PBC. This could have been explained by the wind around the participant, which increased the convection effect. Moreover, the homogeneity of the temperature between the top and bottom of the room was better in the wind chill WBC than in the PBC cabin. This finding could explain the greater decrease in mean skin temperature after exposure in wind chill WBC technology than in PBC. Wind chill WBC technology reduces the presence of a boundary layer and increases heat extraction from the body. The homogeneity of the temperature of exposure allows the entire body to be cooled in a consistent way. In PBC, temperature adjustment is performed by spraying nitrogen when the temperature inside the cabin rises above a certain level (e.g., above −115 °C if the selected temperature of exposure was −120 °C) at the site of the nitrogen nozzle. The amplitude of the temperatures before and after adjustment may range from 10 to 20 °C, making it difficult to set and control precise temperatures and leading to the heterogeneity of the exposure temperature (Bouzigon et al., 2016).

Table 4
Changes in skin temperature after PBC and WBC exposure with different cold producing devices.

Studies	Technology/exposure protocol/ measurement tools	Forehead	Chest	Arms	Abdomen	Thighs	Mean skin temperature
Present study	WBC Cryantal 3 min −40 °C Thermal imaging	−9.5 °C	−9.9 °C	−10 °C	−11.7 °C	−13.6 °C (upper thighs only)	−11.0 °C
Savic et al. (2013) (Savic et al., 2013)	PBC Criomed 3 min −140 °C Thermal imaging		−7.3 °C	−5.7 °C	−11.5 °C		−9.7 °C
Fonda et al. (2014) (Fonda et al., 2014)	PBC Criomed 3 min −140 °C Thermolazer		−6.7 °C	−10.5 °C	−9.3 °C	−12.6 °C	−9.4 °C
Hausswirth et al. (2013) (Hausswirth et al., 2013)	PBC Krion 3 min −160 °C Thermal imaging		−7.1 °C	−7.5 °C			−8.3 °C
Louis et al. (2015) (Louis et al., 2015)	PBC Krion 3 min −160 °C Thermal imaging 1^{rst}exp/3^{rd}exp	−1.2 °C −1.1 °C					−8.2 °C −7.6 °C
Zalewski et al. (2013) (Zalewski et al., 2013)	WBC Stan Mar 3 min −120 °C Thermal imaging		−17.4 °C	R: −19.0 °C L: −21.7 °C	−17.6 °C		
Selfe et al. (2014) (Selfe et al., 2014)	WBC Juka 3 min −135 °C Thermal imaging						−14.8 °C
Cholewka et al. (2012) (Cholewka et al., 2012)	WBC (Unknown model) 3 min −120 °C Thermal imaging	−2.3 °C	−4.9 °C	−5.6 °C			−4.9 °C
Hausswirth et al. (2013) (Hausswirth et al., 2013)	WBC Zimmer 3 min −110 °C Thermal imaging		−12.4 °C	−13.5 °C			−13.7 °C
Louis et al. (2015) (Louis et al., 2015)	WBC Zimmer 3 min −60 °C Thermal imaging 1^{rst}exp/3^{rd}exp	−7.8 °C −7.1 °C					−8.7 °C −7.6 °C
Costello et al. (2012) (Costello et al., 2012)	WBC Zimmer 3 min 40 −110 °C Thermal imaging					R. knee: −8.8 °C L. knee: −9.9 °C	
Costello et al. (2014) (Costello et al., 2014)						−12.1 °C	

(Abbreviations: PBC: Partial body-cryotherapy; WBC: Whole-body cryotherapy; Min: Minute; R: Right, L: Left; Exp: Exposure).

In addition to the efficiency in skin temperature decrease, this technology was interesting because nitrogen was not used. Thus, exposures were safer and less costly. Moreover, this chamber is the first mobile WBC chamber.

The absence of ear canal temperature changes within the 20 min after the exposure was inconsistent with some studies that showed a decrease between 0.2 and 0.3 °C immediately after, 20 min, 40, 50 and 60 min after WBC and PBC exposures (Costello et al., 2014, 2012; Hausswirth et al., 2013; Louis et al., 2015). Westerlund et al. (2003) did not find a decrease in rectal temperature after a 2-min WBC exposure, and Selfe et al. (Selfe et al., 2014) showed no difference in gastrointestinal temperature after 1, 2 and 3 min of WBC exposure. The lack of changes in our study could be explained by the unilaterality of the wind inside the chamber. During the exposure, participants stood with their faces in front of the fans and their backs were not exposed to the cold wind. However, it could be worthwhile to record the ear canal temperature for a longer period. The ear canal temperature could decrease later.

Finally, even if important differences in interindividual thermal sensations were noted, the wind chill WBC technology did not appear to be unpleasant. The reported sensations were uncomfortable, similar to those reported with WBC Zimmer and Juka, but they remained bearable (Selfe et al., 2014; Smolander et al., 2004; Westerlund et al., 2003).

The main limitation of this study was that the measurement of skin temperature was performed only on the front side of the body. The study was conducted within a trailer, and it was not possible to place another camera behind the participants. To maintain the quality of the thermal measurements and avoid extra convection, participants were not allowed to turn their bodies. In this study, participants were placed in front of the fans. Thus, decreases in skin temperature measured in this study did not truly reflect decreases of the entire body. Nevertheless, the study showed the capacity of this technology to decrease skin temperature with fans.

The second limitation was the lack of space in the trailer. In fact, it was impossible to capture the participants' entire body with the thermal camera, which explained the small zone of measurement of the thighs.

5. Conclusions

This new WBC technology based on WCET appeared suitable to induce skin temperature decrease in all of the measured zones of interest. In fact, a 3-min exposure at −40 °C with a forced convection could be as effective as a 3-min exposure at −110 °C to −195 °C in traditional WBC and PBC devices. However, the effects could be improved with the addition of more fans to more effectively cool the entire body (front and back). This technology is interesting because nitrogen is not used, making it safer and less costly to implement. Further studies should be performed to assess the effect of this technology on other variables. Studies on colder temperatures of exposure (e.g., 80 °C, −110 °C) using this new technology are merited.

Conflicts of interest

The first author, Romain Bouzigon, is employed by Cryantal Development as part of a collaboration between the university and

the company. Romain Bouzigon received a grant from the French Government (Grant no. 703/2012).

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