ARTIGO

Effects of Personal Protective Equipment in Chemical, Biological, Radiological and Nuclear Defense on Heart Rate and Heart Rate Variability of the Human Body: a narrative review

Efeitos dos Equipamentos de Proteção Individual em Defesa Biológica, Nuclear, Química e Radiológica sobre a Frequência Cardíaca e a Variabilidade da Frequência Cardíaca em Militares: uma revisão narrativa

ABSTRACT

This study investigates the impacts of Personal Protective Equipment (PPE) used in biological, nuclear, chemical, and radiological defense (CBRN) on the heart rate (HR) and heart rate variability (HRV) of the human body. Studies analyzing the prolonged use of such equipment demonstrate a significant increase in thermal and physiological strain on exposed individuals. The literature review highlights that the encapsulation of PPE hinders heat dissipation, raising HR and reducing HRV, which may compromise workers' responsiveness and safety. Mitigation measures, such as cooling systems and adequate training, are discussed. In conclusion, we have identified that using PPE in CBRN presents significant challenges to the safety and well-being of workers, compromising their physiological capacity for thermal regulation. Elevated heart rate (HR) and reduced heart rate variability (HRV) can negatively impact performance and increase the risk of heat-related collapse. Therefore, mitigating measures, such as cooling systems and adequate training, are relevant strategies to ensure the efficiency of the flight crew's mission.

Keywords: Personal Protective Equipment. Chemical and Biological Defense. Heart Rate. Heart Rate Variability. Thermal Stress.

Laura Cabral Cruz Lopes da Silveira Andrade
Air Force University - UNIFA, Rio de Janeiro, RJ, Brazil
Email: laurabrasil@gmail.com
ORCID: https://orcid.org/0009-0008-7209-599X

Paula Morisco de Sá
Air Force University - UNIFA, Rio de Janeiro, RJ, Brazil
Email: paulamorisco@gmail.com
ORCID: https://orcid.org/0000-0002-7812-1895

Vinicius de Oliveira Damasceno
Air Force University - UNIFA, Rio de Janeiro, RJ, Brazil
Email: viniciusvod@fab.mil.br
ORCID: https://orcid.org/0000-0003-0577-9204

RESUMO

Este estudo investiga os impactos dos Equipamentos de Proteção Individual (EPI) utilizados na defesa biológica, nuclear, química e radiológica (DBNQR) sobre a frequência cardíaca (FC) e a variabilidade da frequência cardíaca (VFC) do corpo humano. Tem o objetivo de traçar os percursos históricos acerca do que está descrito na literatura sobre o tema em questão, e abordar como a encapsulação dos EPIs pode impedir a dissipação de calor, elevando a FC e reduzindo a VFC e comprometendo a capacidade de resposta e a segurança dos trabalhadores. Neste descritivo, foram analisados estudos que demonstram que o uso prolongado desses equipamentos pode aumentar significativamente a carga térmica e fisiológica dos indivíduos expostos. Como conclusão, identificamos que o uso de EPIs em DBNQR impõe desafios significativos para a segurança e bem-estar dos trabalhadores, comprometendo sua capacidade fisiológica de regulação térmica. A elevação da FC e a redução da VFC podem impactar negativamente o desempenho e aumentar os riscos de colapso térmico e que medidas mitigadoras, como sistemas de resfriamento e treinamento adequado, são estratégias que podem ser relevantes para garantir a eficiência da missão da tripulação de voo.

Palavras-chave: Equipamentos de Proteção Individual. Defesa Química e Biológica. Frequência Cardíaca. Variabilidade da Frequência Cardíaca. Estresse Térmico.

Received:	**02 Jun 2025**
Reviewed:	**Jun-Oct 2025**
Received after revised:	**02 Mar 2026**
Accepted:	**03 Mar 2026**

RAN
Revista Agulhas Negras
eISSN (online) 2595-1084

http://ebrevistas.eb.mil.br/aman

1 Introduction

The safety of military personnel exposed to biological, chemical, radiological, and nuclear (CBRN) threats is ensured through the use of Personal Protective Equipment (PPE) (Brasil, 2014). In Aeromedical Evacuation (MEDEVAC) operations—which involve the removal and air transport of patients in critical situations from an unassisted location to another where they can receive proper treatment (Brasil, 2020; Brasil, 2022c)—it is essential for all crew members to use PPE to protect them from contamination in the event of a CBRN threat (Brasil, 2014). This PPE, designed to encapsulate the body, consists of protective layers that prevent the penetration of hazardous substances (Brasil, 2014).

In MEDEVAC operations involving rotary-wing aircraft, all crew members must wear PPE, and once donned, they cannot safely remove the equipment until the mission is concluded, as it is not possible to establish a decontamination zone within these aircraft (Brasil, 2016; Brasil, 2024). Consequently, the prolonged use of such equipment in this type of aircraft presents significant challenges: difficulty in dissipating body heat, the impossibility of removing the gear, and the inability to hydrate (Yokota; Karis; Tharion, 2014; Bogerd; Langenberg; DenHartog, 2018).

This specific scenario leads to an increase in core body temperature and dehydration, raising the risk of heat-related illnesses such as edema, cramps, exhaustion, and heatstroke (McArdle; Katch, I.; Katch, L.; 2016; Bein, 2024). The increase in fluid loss causes an elevated heart rate (HR) and a decrease in heart rate variability (HRV) (Jovanovic et al., 2014; Maley et al., 2020; Seo et al., 2018; Yokota; Karis; Tharion, 2014), resulting in physiological strain on the cardiovascular system. Furthermore, it intensifies symptoms such as thirst, fatigue, sensations of lightheadedness, and visual disturbances, all of which can compromise operational performance (McArdle; Katch, I.; Katch, L., 2016).

Given this context, it is crucial to understand the effects of CBRN PPE on heat dissipation, HR, and HRV to develop strategies that mitigate thermal stress and its physiological impacts. Furthermore, this study aims to analyze records from scientific and military literature addressing the influence of this equipment on the parameters and their potential consequences for operational performance.

2 Theoretical framework

2.1 The Brazilian Air Force and actions in CBNR

The Ministry of Aeronautics—the current Brazilian Air Force (FAB)—was established in 1941 through Decree-Law 2,961, signed by then-President Getúlio Vargas (Diário Oficial da União, 1941). In 1987, 46 years later, Brazil experienced its first CBRN event: a severe radiological accident involving Caesium-137 in Goiânia, Goiás. The accident was reported after a radiotherapy device was found in an abandoned clinic; the device was dismantled and distributed, causing radioactive contamination that severely affected the health of hundreds of people. Classified as Level 5 on the International Nuclear Event Scale (INES), it remains Brazil's largest radioactive incident and the largest in the world occurring outside a nuclear power plant (Brasil, 2014; Queiroga, 2022).

At the time, the Ministry of Aeronautics was called upon to transport contaminated materials and personnel to Rio de Janeiro and other locations. However, the aircrew and support teams were not adequately trained or equipped, resulting in grave health effects that persist to this day. During that crisis, the FAB was also involved in the transport of fatalities in lead-lined concrete caskets (Brasil, 2014).

In 2010, the FAB organized the 1st Workshop on CBRN Defense, highlighting the need for constant technological and logistical updates. In 2013, the FAB again demonstrated its readiness by providing support to the victims of the Kiss nightclub fire in Santa Maria, Rio Grande do Sul. This operation involved 91 missions using 12 aircraft and the deployment of the country's largest airborne ICU within the C-105 Amazonas aircraft (Brasil, 2014).

In 2020, the FAB conducted several operations to combat the COVID-19 pandemic:

> Operating daily in the fight against the pandemic since 2020, the FAB has logged approximately 6,000 flight hours as part of Operation COVID-19, launched on March 20, 2020. All operational activities were maintained 24 hours a day, including air operations, airspace defense and control, and logistical and security activities. In support of the national healthcare system, the FAB also facilitated the transport of over 5,000 tons of cargo—including medical supplies and oxygen—to the Northern region of the country, as well as the transport of hundreds of patients and millions of doses of COVID-19 vaccines (Força Aérea Brasileira, 2022, own translation).[1]

Currently, CBRN MEDEVAC within the FAB is supported by the following documents: DCA 1-6 (2014a), DCA 1-6 (2024), and the Joint Technical Note (2016). It is observed, therefore, that the FAB conducts CBRN operations defined as the "action consisting of employing Air Force

[1] Original Text: *Atuando, diariamente, no combate à pandemia, desde 2020, a FAB já contabilizou cerca de 6 mil horas voadas na Operação COVID-19, deflagrada em 20 de março de 2020. Todas as atividades operacionais foram mantidas 24 horas por dia, como as operações aéreas, a defesa e controle do espaço aéreo e as atividades logísticas e de segurança. Em auxílio ao Sistema de Saúde nacional, a FAB também promoveu o transporte de mais de 5 mil toneladas de cargas, entre insumos e oxigênio, para a região Norte do País, de centenas de pacientes e de milhões de doses de vacinas contra a COVID-19.*

assets to remove injured or sick persons to locations where they can receive adequate assistance" (Brasil, 2022c, p. 7), even when not structurally prepared.

DCA 1-6 (2014) addresses the flight suit used as PPE in CBRN environments to enable safer engagement for aircrews and illustrates protection levels A, B, C, or D:

> Level A protective clothing: Provides maximum protection; fully encapsulated suits utilizing a self-contained breathing apparatus (SCBA). Designed for skin and respiratory protection against gases and microorganisms (effective for CBRN agents).
> Level B protective clothing: Encapsulated or non-encapsulated suits designed for skin and respiratory protection against li[2]quids (effective for CRN agents).
> Level C protective clothing: Suits designed for skin and respiratory protection against solid particles or splashes of liquid products (effective for RN and some C agents). Activated carbon suits belong to this category, as well as Tyvek suits.
> Level D protective clothing: Suits designed for partial protection against solid particles or splashes of liquid products (Brasil, 2014, p.13, own translation).

Crew protection equipment is classified according to the type and operation of each aircraft. In the case of CBRN protective suits, they must provide at least Level C protection (Brasil, 2014), such as the Saratoga Blücher Technologies suit used by the FAB as CBRN PPE. This suit is manufactured from a textile composite of two air-permeable fabric layers (outer and inner). The outer layer is impregnated with an oil and water-repellent treatment, while the inner layer is a filter laminate base, subdivided into three additional layers: the cover layer, the adsorbent layer of activated carbon spheres (closest to the outer fabric), and the knitted mesh fabric layer, which is closest to the skin (Blücher, 2013).

Brazilian legislation recommends that the use of such clothing "must not compromise the mobility of the crew, especially the pilots, to the point of jeopardizing flight safety" (Brasil, 2014, p. 25). However, in addition to the suit, aircrew members must wear masks (compatible with the communication system), breathing equipment, boots, and gloves (Brasil, 2014). There are reports in the literature of possible associations between the use of this PPE and the degradation of crew performance (Thornton; Brown; Redman, 1985; NATO, 2004).

Regarding the use of CBRN PPE within the FAB, the 3rd/8th GAv (Puma Squadron), which operates the Eurocopter EC725 (H-36 Caracal) helicopter, includes a specific qualification subprogram (SPQE-8) for flight with CBRN equipment in its Operational Upgrade Program

[2] Original Text: *Roupas de proteção nível A: proteção máxima, totalmente encapsuladas, utiliza sistema de respiração autônoma, destinado à proteção cutânea e das vias respiratórias contra gases, e microrganismos (eficaz para agentes QBRN). Roupas de proteção nível B: roupas encapsuladas ou não, destinadas à proteção cutânea e das vias respiratórias contra líquidos (eficaz para agentes QRN). Roupas de proteção nível C: roupas para proteção cutânea e das vias respiratórias contra partículas sólidas ou respingos de produtos líquidos (eficaz para agentes RN e alguns Q). As roupas de carvão ativado pertencem a esta categoria, assim como a roupa Tyvec. Roupas de proteção nível D: roupas para proteção parcial contra partículas sólidas ou respingos de produtos líquidos.*

(INPREP/PEVOP/14C). This specialization includes the qualification of pilots and aircrews in CBRN operations using the specific aircrew PPE prescribed in DCA 1-6 (2014) (Brasil, 2022a).

The activities performed by crew members on board an aircraft go beyond psychomotor skills, also encompassing technical flight skills and non-technical psychological skills. In this Air Unit (UAE), pilots manage systems, plan routes, monitor weather conditions, maintain communication with air traffic control, and organize the cockpit, in addition to flying the aircraft.

Crew members, such as mechanics and equipment operators, assist pilots with technical aspects of the aircraft, providing guidance during takeoffs and landings. Due to their greater mobility, they can better observe obstacles by leaning outside the helicopter, while also managing movement within the cargo or passenger cabin. Each performs their respective functions according to their training and operational maintenance (Brasil, 2022a).

Regarding the specific skills required for CBRN MEDEVAC flights, in addition to what was previously mentioned, adaptation to the type of clothing is necessary (Brasil, 2022a). In this Air Unit, the CBRN protective suit is worn over the conventional (flame-retardant) flight suit, following NATO recommendations. This practice is related to the protection factor, as evidenced in studies on combinations of uniforms and PPE (Bogerd; Langenberg; DenHartog, 2018).

2.1 Human Physiology and CBRN PPE Use Through Experimental Studies

In 2004, NATO published a guide regarding the influence of CBRN PPE on individual performance. To measure this, PPE types were classified into "low," "medium," and "high" protection categories. The first category is the simplest, consisting of a conventional uniform and mask, while the latter is the most complex, comprising all available equipment: protective suit, mask, gloves, and boots (NATO, 2004).

The use of PPE combinations with various protective gear was studied by Bogerd, Langenberg, and DenHartog (2018). Their study established a relationship between the safety factor associated with overlapping protective layers and hyperthermia risk; specifically, the more secure the clothing against CBRN agents, the higher the associated risk of hyperthermia (Bogerd; Langenberg; DenHartog, 2018). The fact that PPE increases skin isolation from the external environment and possesses low water vapor permeability hinders heat loss through evaporation (NATO, 2004; Yokota; Karis; Tharion, 2014).

The increase in risks associated with the body's lack of compensation regarding core temperature depends on factors such as the type of activity, clothing, weight carried, hydration level, the individual's acclimatization state, as well as physical condition, fatigue, and weather conditions (NATO, 2004). Regarding hydration, it has been shown that being hydrated and/or rehydrating during exertion increases adaptation, tolerance, and endurance while wearing PPE. However, this is ineffective when an uncompensable limit of thermal stress is reached (Cheung; Mclellan, 1998), as electrolyte replacement has a marginal influence on the heat storage rate and is no longer capable of compensating for body temperature (Mclellan; Cheung, 2000).

Latzka et al. (1998) investigated the efficacy of hyperhydration with glycerol and water prior to exercise on heat tolerance and cardiovascular strain during induced, uncompensable heat stress. Volunteers underwent a heat acclimatization protocol, walking at 45% of maximal oxygen consumption (VO_{2MAX}) on a treadmill, performing two 50-minute sessions separated by a 10-minute rest interval. This protocol was followed by a 6-to-10-day period in a hot, dry environment (35°C ambient temperature, 45% relative humidity, 25°C dew point, and 1 m/s air velocity) (Latzka et al., 1998).

The results indicated that glycerol hyperhydration provided a slight increase in exercise duration compared to conventional hydration, but without a significant difference relative to water hyperhydration. Furthermore, none of the hyperhydration methods significantly influenced core temperature, sweat rate, cardiac output, blood pressure, total peripheral resistance, or thermal tolerance. Exhaustion occurred under heat stress conditions, with core and skin temperatures being similar across all tested conditions. However, the benefit of hyperhydration lies in delaying the adverse effects of hypohydration (Latzka et al., 1998). Complementing this, Rubenstein et al. (2017) demonstrated that hypohydration can cause perceptible impacts with a fluid loss of only 2% of body weight. In the study by Latzka et al. (1998), only one participant reached this level of dehydration.

In search of strategies to mitigate thermal stress effects, a study conducted in Serbia evaluated the use of PPE in a CBRN environment, with and without cooling systems, during a 45-minute test. In the group without cooling (NO COOL), two volunteers completed the test without significant changes in subjective heat perception, while seven stopped due to intolerable subjective exertion, and one participant had the test terminated upon reaching the maximum body temperature limit (tympanic temperature exceeding 39.5°C) (Jovanovic et al., 2014). In contrast, in the group using cooling systems, 85% of participants completed the test without reaching the thermal barrier. The average exercise duration was extended by 10 minutes compared to the non-cooling condition (Jovanovic et al., 2014).

Regarding the environment, it is fundamental to consider thermal variation in the workplace. According to Butler et al. (2023), exercise and physical exertion in hot and humid conditions affect human performance and can place the individual at risk of thermal stress. High air humidity influences the sweat rate by limiting the evaporation rate, causing body temperature to rise rapidly (Baker, 2019; Klompmaker et al., 2023).

Thus, to regulate body temperature, it is relevant to understand the process responsible for maintaining a dynamic equilibrium within the body, keeping the internal environment relatively constant, known as homeostasis (Power; Howley, 2014). This means that despite variations in the external environment, the body can regulate its internal processes to keep temperature and other parameters within limits favorable to life (Power; Howley, 2014).

In addition to homeostasis, thermoregulation represents the human body's ability to regulate temperature to ideal conditions, which is around 36.6°C (Périard et al., 2021), or generalized in studies as 37°C. According to the literature, values below 35°C are considered hypothermia (Powers; Howley, 2014), while those above 40.5°C are considered hyperthermia (Savioli et al., 2022).

The organism's primary regulation center is the human brain, which, through the hypothalamus, acts as an internal thermostat that receives signals from the body and adjusts physiological responses to maintain adequate body temperature. When this temperature exceeds the desired level, the body triggers regulatory mechanisms such as vasodilation and sweating to cool down. Conversely, if the temperature is below ideal, the body may induce shivering to increase metabolism and generate heat. These processes ensure the body maintains thermal balance even in adverse environmental conditions (McArdle; Katch, I.; Katch, L., 2016).

Therefore, for body equilibrium to occur, it is essential that some physiological (e.g., climate), pathological (e.g., fever), or pharmacological (e.g., chemotherapy) factor perturbs the organism, triggering hypothalamic responses to ensure survival (MacDonald et al., 2023). In environments below 36°C, heat loss can be quite effective through convection, radiation, and evaporation. However, in environments above this temperature—where the ambient temperature exceeds body temperature—these mechanisms transform into means of gaining energy when wearing CBRN PPE (NATO, 2004).

Furthermore, normal bodily processes also contribute to equilibrium disruption and increased internal temperature, including the basal metabolic rate (BMR), muscular activity, hormones, the thermic effect of food, postural changes, and the environment (McArdle; Katch, I.; Katch, L., 2016). When the body begins to generate enough energy to exceed the thermal equilibrium range without proper compensation, thermal stress manifests (McArdle; Katch, I.; Katch, L., 2016).

The progressive increase in body temperature can lead to physiological problems when cardiovascular compensation fails, including cramps, heat exhaustion, and heatstroke—these being the primary manifestations in increasing order of severity (McArdle; Katch, I.; Katch, L.; 2016; Bein, 2024). Common responses also include vasodilation, perspiration, tachycardia, "renal stress" due to dehydration, and organ dysfunction caused by reduced blood flow (McArdle; Katch, I.; Katch, L.; 2016; Bein, 2024).

Literature highlights the thermal and cardiovascular challenges of using CBRN PPE, considering that these suits limit heat dissipation and increase the physiological load on users (Havenith; Den Hartog; Martini, 2011). Thornton, Brown, and Redman (1985) were among the first to investigate the thermal load imposed by this equipment on aircrews, contributing to subsequent studies. Jovanovic et al. (2014) demonstrated that PPE use can elevate HR and reduce HRV, intensifying physiological stress.

More recent studies, such as those by Seo et al. (2018) and Maley et al. (2020), suggest that strategies like cooling vests and thermal acclimatization can mitigate these effects, although their efficacy is limited by the suits' impermeability. Yokota, Karis, and Tharion (2014) analyzed the autonomic response to thermal stress and found that decreased HRV reflects higher sympathetic activation and lower recovery potential, increasing the risk of thermal collapse (Power; Howley, 2014).

In this context, Soares' (2024) dissertation on HRV in military pilots reinforces the use of this indicator as a tool to evaluate workload in high-demand operational environments. The author demonstrates that changes in autonomic modulation during aerial activity reflect the physical and mental demands imposed on pilots, making HRV a sensitive indicator of both autonomic recovery and the impact of prolonged exposure to operational stress (Soares, 2024).

3 Methodological Path

The present review was based on experimental studies that analyzed the physiological effects of CBRN PPE use under different environmental conditions (Jovanovic et al., 2014; Maley et al., 2020; Seo et al., 2018; Yokota; Karis; Tharion, 2014). Studies that monitored the HR, HRV, and body temperature of individuals equipped with PPE in both simulated and real work environments were considered (Jovanovic et al., 2014; Maley et al., 2020; Seo et al., 2018; Yokota; Karis; Tharion, 2014), alongside a textbook (Power; Howley, 2014) and a master's dissertation (Soares, 2024).

Research from these sources was conducted using electronic scientific databases, such as the National Library of Medicine (MEDLINE) and the Virtual Health Library of the Ministry of Health. In the search, CBRN PPE was utilized as the independent variable, while the dependent variables included factors related to mental and physical fatigue. The descriptors were selected from the Health Sciences Descriptors (DeCS) and Medical Subject Headings (MeSH) databases.

Regarding the FAB (Brazilian Air Force), official documents were utilized, including DCA 1-1/ VOL II (Brasil, 2020), concerning the Basic Doctrine for the Use of the Force; DCA 1-6 (2014), concerning CBRN Mission Doctrine (Brasil, 2014), which, despite having been revoked, still contains relevant information regarding protective suits; and DCA 1-6 (2024), regarding the managerial aspects and concepts of a CBRN mission (Brasil, 2024), the text of which provides relevant information previously addressed in the Joint Technical Standard used for the 2016 Olympic and Paralympic Games (Brasil, 2016).

Furthermore, NSCA 160-6, which addresses MEDEVAC and Airborne ICU operations (Brasil, 2022), and the North Atlantic Treaty Organization (NATO) document ATP-65 (2004)—which deals with protective uniforms and their human wear factor in relation to workload, time, humidity, and garment composition (NATO, 2004)—serve as complementary documents for operations against CBRN threats.

4 Results and Discussion

The use of PPE in CBRN environments imposes significant challenges to the thermal regulation of the human body. Studies demonstrate that utilizing these suits creates an environment of uncompensable heat stress, directly impacting the cardiovascular load of the users (Havenith; DenHartog; Martini, 2011; Richmond et al., 2013; Yokota; Karis; Tharion, 2014; Bogerd; Langenberg; DenHartog, 2018).

Through research in scientific databases, six studies were found regarding the use of body cooling systems or methods (pre- and/or during activities), which explicitly mention active cooling methods such as ice vests or phase-change materials, immersion of hands or forearms in cold water, or ingestion of cold beverages (House; Holmes; Allsopp, 1997; House et al., 2003; Khomenok et al., 2008; Kenny et al., 2011; Jovanovic et al., 2014; Maley et al., 2020). Three studies were identified that directly address the impact of hydration on heat tolerance and the reduction of thermal strain (Cheung; Mclellan, 1998; Mclellan; Cheung, 2000; Rubenstein et al., 2017). Another three studies explore the influence of garment permeability and ventilation (porosity, vapor permeability, or adjustment of clothing layers) and how they influence thermal stress (Havenith; DenHartog; Martini, 2011; Godsmark et al., 2018; Bogerd; Langenberg; DenHartog, 2018). Finally, ten analyzed studies address the general theme of CBRN protective clothing as the primary factor related to elevated thermal strain (Mclellan; Aoyagi, 1996; Mclellan; Cheung, 2000; Brasser, 2010; Havenith; Den Hartog; Martini, 2011; Richmond et al., 2013; Jovanovic et al., 2014; Yokota; Karis; Tharion, 2014; Rubenstein et al., 2017; Seo et al., 2018; Maley et al., 2020).

The study by Havenith, Den Hartog, and Martini (2011) evidenced that the thermal insulation and low water vapor permeability of PPE limit heat dissipation, increasing the thermal load and, consequently, the cardiovascular response. This impact is reflected in an increased heart rate (HR), which rises to compensate for the lower efficiency of sweating and the reduction of heat dissipation through the skin (Havenith; DenHartog; Martini, 2011).

Bogerd, Langenberg, and DenHartog (2018) reinforce this conclusion, demonstrating that the restriction of sweat evaporation and the resistance to airflow within the microclimate created by the PPE contribute to a progressive rise in HR, even at moderate workloads. This increase is a reflection of sympathetic nervous system activation, leading to greater cardiovascular effort to maintain thermal homeostasis (Power; Howley, 2014).

Under extreme heat conditions, HR can increase by up to 50% compared to resting values during prolonged PPE use, as demonstrated by Richmond et al. (2013). In studies conducted by Yokota, Karis, and Tharion (2014), it was found that heart rate variability (HRV)—an important indicator of the autonomic response to thermal stress—underwent a significant reduction in individuals exposed to these conditions. The decrease in HRV is associated with greater sympathetic activation and lower parasympathetic modulation, suggesting cardiovascular overload and reduced recovery capacity (Yokota; Karis; Tharion, 2014).

Kenny et al. (2011) reported that, under high-temperature conditions, HR can reach peaks of up to 170 bpm, while HRV is drastically reduced, suggesting a state of exacerbated autonomic stress. This effect suggests a decrease in the body's ability to adapt to thermal stress over time, increasing the risk of adverse events such as heat exhaustion and cardiovascular collapse (Kenny et al., 2011).

Certain cooling measures have been suggested as effective strategies to mitigate these effects. Studies by Maley et al. (2020) indicate that pre-cooling and active cooling methods during work—such as the use of cooling vests and hand immersion in cold water—help reduce HR and improve heat tolerance. These methods have been shown to extend safe working time in hot environments and minimize the impact of thermal stress on the cardiovascular system (Maley et al., 2020).

The study by Khomenok et al. (2008) also reinforces this evidence, showing that immersing hands in cold water during rest periods significantly reduces HR and improves the sensation of thermal comfort, extending work capacity in extreme heat. Additionally, research by Seo et al. (2018) indicates that heat acclimatization over five days can reduce cardiovascular load, but the use of PPE still represents a limiting factor for complete adaptation, as the findings were not statistically significant.

Nevertheless, operational characteristics in the FAB are restricted regarding the means that can be used to mitigate the effects of PPE use. During flight, the use of water immersion, certain cooling methods, or halting flight operations to establish an acclimatization program for situations and training that are infrequent within the FAB may become impractical, considering the management of errors and threats that affect flight safety (Brasil, 2022b).

Thus, scientific evidence suggests that using PPE in CBRN environments imposes significant thermal and cardiovascular stress, reducing thermoregulatory efficiency and increasing cardiac workload (Havenith et al., 2011; Richmond et al., 2013; Yokota; Karis; Tharion, 2014; Bogerd; Langenberg; Denhartog, 2018). Strategies such as active cooling and thermal acclimatization can help attenuate these effects, but the efficacy of these interventions varies and depends on environmental conditions and the duration of heat exposure (Khomenok et al., 2008; Kenny et al., 2011; Seo et al., 2018; Maley et al., 2020).

Furthermore, HRV has been utilized as a sensitive indicator of the autonomic response to thermal stress, reflecting adaptations of the autonomic nervous system in different operational scenarios (Soares, 2024). Studies such as Soares (2024) demonstrate that HRV can be employed to characterize the physiological workload of military pilots during aerial activity, providing relevant insights into autonomic recovery and the impacts of prolonged physical and mental stress.

The main findings have been systematized in Table 1.

Table 1- Systematization of Results from the Review

Primary outcome	**Impact / Effect**	**Citation (Author, Year)**
Thermal insulation and low permeability of PPE	Limited heat dissipation, increasing thermal load and raising HR to compensate for inefficient sweating.	Havenith; DenHartog; Martini (2011)
Restriction of sweat evaporation and air flow	They contributed to a progressive increase in HR, even at moderate workloads, reflecting activation of the sympathetic nervous system and greater cardiovascular effort.	Bogerd; Langenberg; DenHartog (2018)
Extreme increase in HR	HR increased by up to 50% compared to resting values during prolonged use of PPE in extreme heat conditions.	Richmond *et al.* (2013)
Reduction in HRV	HRV was significantly reduced, indicating greater sympathetic activation and less parasympathetic modulation, suggesting cardiovascular overload and reduced recovery capacity.	Yokota; Karis; Tharion (2014)
HR peaks and dramatic reduction in HRV	HR reached peaks of 170 bpm, while HRV decreased dramatically, suggesting a state of exacerbated autonomic stress and increased risk of heat exhaustion/cardiovascular collapse.	Kenny *et al.* (2011)

Primary outcome	Impact / Effect	Citation (Author, Year)
Effectiveness of active cooling methods	Pre-cooling and active cooling (thermal vests, immersing hands in cold water) during work helped reduce HR and improved heat tolerance, extending safe working time.	Maley *et al.* (2020)
Immersion of hands in cold water	During rest periods, it significantly reduced HR and improved thermal comfort, prolonging the ability to work in extreme heat.	Khomenok *et al.* (2008)
Effect of heat acclimatization	Acclimatization to heat reduced cardiovascular load, but the use of PPE remained a limiting factor for complete adaptation (the result found was not significant).	Seo *et al.* (2018)
VFC as a Physiological Load Indicator	HRV can be used to characterize the physiological workload of military pilots during flight activity, providing insights into autonomic recovery.	Soares (2024)

Legenda: EPIs, equipamentos de proteção individual; FC, Frequência Cardíaca; VFC, variabilidade da frequência cardíaca.

Source: The authors

5 Conclusions

The use of CBRN PPE imposes significant challenges to the safety and well-being of military personnel, compromising their physiological capacity for thermal regulation. The elevation in HR and the reduction in HRV can negatively impact performance and increase the risk of thermal collapse (Power; Howley, 2014). To mitigate the adverse effects resulting from the use of PPE in CBRN environments, it is essential to adopt measures such as improvements in equipment design and specialized training. The results of this study may contribute to the establishment of new operational protocols, as well as suggestions for PPE design and preventive training to mitigate thermal effects. Furthermore, the importance of implementing strategies such as active cooling and the optimization of operational protocols is emphasized, with the objective of reducing thermal and cardiovascular strain in extreme environments.

References

BEIN, T. Pathophysiologie und Management der Hitzeerkrankung. **Medizinische Klinik, Intensivmedizin und Notfallmedizin**, v. 119, n. 5, p. 373–380, 2024. Disponível em: https://link.springer.com/article/10.1007/s00063-023-01072-1, Access on: 23 May 2025.

BLÜCHER GmbH. **Instruction manual:** CBRN protective coverall POLYPROTECT 12. Erkrath: Blücher GmbH, 2013. Disponível em: https://www.manualslib.com/manual/2063568/Blucher-Saratoga-Cbrn-Protective-Coverall.html?page=3. Access on: 21 May 2025.

BOGERD, C. P.; LANGENBERG, J. P.; DENHARTOG, E. A. A novel adjustable concept for permeable gas/vapor protective clothing: Balancing protection and thermal strain. **Annals of Work Exposures and Health**, v. 62, n. 2, p. 232–242, 2018. Disponível em: https://doi.org/10.1093/annweh/wxx101. Access on: 10 May 2025.

BAKER, L. B. Physiology of sweat gland function: The roles of sweating and sweat composition in human health. **Temperature**, v. 6, n. 3, p. 211–259, 2019. Disponível em: https://pmc.ncbi.nlm.nih.gov/articles/PMC6773238/. Access on: 10 May 2025.

BRASSER, P. Optimizing the protection against the physiological burden of CBRN clothing. **International Journal of Occupational Safety and Ergonomics**, v. 16, n. 2, p. 153–168, 2010. Disponível em: https://doi.org/10.1080/10803548.2010.11076836. Access on: 10 May 2025.

BRASIL. Ministério da Defesa. Comando Da Aeronáutica. **DCA 1-1/Vol II:** Doutrina Básica da Força Aérea Brasileira - Volume 2. Brasília, 2020.

BRASIL. Ministério da Defesa. Comando Da Aeronáutica. **DCA 1-6:** Doutrina De Preparo E Emprego Da Fab Em Missões De Transporte Na Defesa Química, Biológica, Radiológica E Nuclear (DQBRN). Brasília, 2014.

BRASIL. Ministério da Defesa. Comando Da Aeronáutica. **DCA 1-6:** Doutrina De Defesa Biológica Nuclear Química e Radiológica (DBNQR). Brasília, 2024.

BRASIL. Ministério da Defesa. Comando da Aeronáutica. Instrução do Comando de Preparo sobre o Programa de Elevação Operacional nº 14C (INPREP/PEVOP/14C) - **Programa de Elevação Operacional - PEVOP H-36**. Brasília, 2022a.

BRASIL. Ministério da Defesa. Comando Da Aeronáutica. **MCA 3-10:** Manual do Facilitador de CRM (Corporate Resource Management) da Força Aérea Brasileira. Brasília, 2022b.

BRASIL. Ministério da Defesa. Comando Da Aeronáutica. **NSCA 160-6:** Evacuação Aeromédica (EVAM) e UTI-Aérea da Aeronáutica**.** Brasília, 2022c.

BRASIL. Ministério da Saúde. Ministério da Ciência, Tecnologia e Inovação. Ministério da Defesa. Nota Técnica conjunta. **Estrutura de atendimento às ameaças, incidentes ou ataques de natureza química, biológica, radiológica e nuclear no período dos jogos Rio 2016.** Brasília, 2016.

BUTLER, C. *et al.* Current clinical concepts: Heat tolerance testing. **Journal of athletic training**, v. 58, n. 2, p. 84–90, 2023. Disponível em: https://pmc.ncbi.nlm.nih.gov/articles/PMC10072087/. Access on: 10 May 2025.

CHEUNG, S. S.; MCLELLAN, T. M. Influence of hydration status and fluid replacement on heat tolerance while wearing NBC protective clothing. **European journal of applied physiology and occupational physiology**, v. 77, n. 1–2, p. 139–148, 1998. Disponível em: https://link.springer.com/article/10.1007/s004210050312. Access on: 19 May 2025.

FORÇA AÉREA BRASILEIRA. **A FAB e o combate à pandemia de COVID-19 em 2021**. Disponível em: https://www.fab.mil.br/noticias/mostra/38481/OPERA%C3%87%C3%83O%20COVID-19%20-%20A%20FAB%20e%20o%20combate%20%C3%A0%20pandemia%20de%20COVID-19%20em%202021. Access on: 20 May 2025.

GODSMARK, C. N. *et al.* Moisture vapour permeable gloves extend thermal endurance and safe work time more than other similarly permeable chemical-biological ancillary protective items. **Ergonomics**, v. 61, n. 12, p. 1635–1645, 2018. Disponível em: https://doi.org/10.1080/00140139.2018.1503726. Access on: 19 May 2025.

HAVENITH, G.; DEN HARTOG, E.; MARTINI, S. Heat stress in chemical protective clothing: porosity and vapour resistance. **Ergonomics**, v. 54, n. 5, p. 497–507, 2011. Disponível em: https://doi.org/10.1080/00140139.2011.558638. Access on: 19 May 2025.

HOUSE, J. R. *et al.* Testing the effectiveness of techniques for reducing heat strain in Royal Navy nuclear, biological and chemical cleansing stations' teams. **Journal of the Royal Naval Medical Service**, v. 89, n. 1, p. 27–34, 2003. Disponível em: https://pubmed.ncbi.nlm.nih.gov/14655424/ . Access on: 19 May 2025.

HOUSE, J. R.; HOLMES, C.; ALLSOPP, A. J. Prevention of heat strain by immersing the hands and forearms in water. **Journal of the Royal Naval Medical Service**, v. 83, n. 1, p. 26–30, 1997. Disponível em: https://pubmed.ncbi.nlm.nih.gov/9282438/. Access on: 19 May 2025.

JOVANOVIC, D. *et al.* Physiological tolerance to uncompensated heat stress in soldiers: Effects of various types of body cooling systems. Vojnosanitetski pregled. **Military-medical and pharmaceutical review**, v. 71, n. 3, p. 259–264, 2014. Disponível em: https://doiserbia.nb.rs/Article.aspx?ID=0042-84501300045J. Access on: 19 May 2025.

KENNY, G. P. *et al*. Ice cooling vest on tolerance for exercise under uncompensable heat stress. **Journal of Occupational and Environmental Hygiene**, v. 8, n. 8, p. 484–491, 2011. Disponível em: https://doi.org/10.1080/15459624.2011.596043. Access on: 23 May 2025.

KHOMENOK, G. A. *et al.* Hand immersion in cold water alleviating physiological strain and increasing tolerance to uncompensable heat stress. **European journal of applied physiology**, v. 104, n. 2, p. 303–309, 2008. Disponível em: https://link.springer.com/article/10.1007/s00421-008-0693-y. Access on: 7 Jun. 2025.

KLOMPMAKER, J. O. *et al.* Long-term exposure to summer specific humidity and cardiovascular disease hospitalizations in the US Medicare population. **Environment international**, v. 179, n. 108182, p. 108182, 2023. Disponível em: https://www.sciencedirect.com/science/article/pii/S0160412023004555?via%3Dihub. Access on: 7 Jun. 2025.

LATZKA, W. A. *et al.* Hyperhydration: tolerance and cardiovascular effects during uncompensable exercise-heat stress. **Journal of applied physiology** (Bethesda, Md.: 1985), v. 84, n. 6, p. 1858–1864, 1998. Disponível em: https://doi.org/10.1152/jappl.1998.84.6.1858. Access on: 7 Jun. 2025.

MACDONALD, R. C. *et al.* Consideration of the importance of measuring thermal discomfort in biomedical research**. Trends in molecular medicine**, v. 29, n. 8, p. 589–598, 2023. Disponível em: https://pmc.ncbi.nlm.nih.gov/articles/PMC10619709/. Access on: 12 junho 2025.

MALEY, M. J. *et al.* Extending work tolerance time in the heat in protective ensembles with pre- and per-cooling methods. **Applied Ergonomics**, v. 85, p. 103064, 2020. Disponível em:

https://www.sciencedirect.com/science/article/abs/pii/S0003687018306379?via%3Dihub. Access on: 12 Jun. 2025.

MCARDLE, W.; KATCH, I.; KATCH, L. **Fisiologia do Exercício:** Nutrição, Energia e Desenvolvimento Humano. 8. ed. Rio de Janeiro: Guanabara Koogan, 2016.

MCLELLAN, T. M.; AOYAGI, Y. Heat strain in protective clothing following hot-wet or hot-dry heat acclimation. **Canadian journal of applied physiology**, v. 21, n. 2, p. 90–108, 1996. Disponível em: https://cdnsciencepub.com/doi/10.1139/h96-009. Access on: 12 Jun. 2025.

MCLELLAN, T. M.; CHEUNG, S. S. Impact of fluid replacement on heat storage while wearing protective clothing. **Ergonomics**, v. 43, n. 12, p. 2020–2030, 2000. Disponível em: https://doi.org/10.1080/00140130050201454. Access on: 19 Jun. 2025.

NORTH ATLANTIC TREATY ORGANIZATION (NATO). ATP-65 - The effect of wearing NBC individual protection equipment on individual and unit performance during military operations. **NATO Standardization Agency (NSA)**, 2004.

PÉRIARD, J. D.; *et al*. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. **Physiological reviews**, v. 101, n. 4, p. 1873–1979, 2021. Disponível em: https:// https://journals.physiology.org/doi/full/10.1152/physrev.00038.2020. Access on: 12 Jun. 2025.

POWERS, S.; HOWLEY, E. **Fisiologia do Exercício:** teoria e aplicação ao condicionamento e ao desempenho. 8. ed. Barueri: Manole, 2014.

QUEIROGA, M. M. V. O Sistema de Defesa Biológica, Nuclear, Química E Radiológica E A Contribuição Para A Pronta Resposta Da Força Aérea Brasileira. **Escola Superior de Guerra.** Rio de Janeiro, 2022. Disponível em: https://repositorio.esg.br/bitstream/123456789/1618/1/CAEPE.59%20TCC%20VC.pdf. Acesso em 26 fev. 2026.

RICHMOND, V. L. *et al.* Insulated skin temperature as a measure of core body temperature for individuals wearing CBRN protective clothing. **Physiological measurement**, v. 34, n. 11, p. 1531–1543, 2013. Disponível em: https://iopscience.iop.org/article/10.1088/0967-3334/34/11/1531. Access on: 29 Jun. 2025.

RUBENSTEIN, C. D. *et al.* Fluid replacement advice during work in fully encapsulated impermeable chemical protective suits. **Journal of occupational and environmental hygiene**, v. 14, n. 6, p. 448–455, 2017. Disponível em: https://doi.org/10.1080/15459624.2017.1296230. Access on: 29 Jun. 2025.

SAVIOLI, G. *et al.* Heat-related illness in emergency and critical care: Recommendations for recognition and management with medico-legal considerations. **Biomedicines**, v. 10, n. 10, p. 2542, 2022. Disponível em: https://pmc.ncbi.nlm.nih.gov/articles/PMC9599879/. Access on: 2 Jun. 2025.

SEO, Y. *et al*. Effects of 5-Day Heat Acclimation on Workers Wearing Personal Protective Clothing. **Journal of Exercise and Nutrition**, v.1, n.1, 2018. Disponível em: https://pmc.ncbi.nlm.nih.gov/articles/PMC10194072/. Access on: 12 Jun. 2025.

SOARES, A. B. F. **Variabilidade da Frequência Cardíaca em Pilotos Militares Durante a Atividade Aérea:** Uma Revisão de Escopo. 2024, 98 p. Dissertação (Mestrado em Desempenho Humano Operacional) - Universidade da Força Aérea, Brasil, 2024.

THORNTON, R.; BROWN, G. A.; REDMAN, P. J. The effect of the UK aircrew chemical defence assembly on thermal strain. **Aviation, space, and environmental medicine**, v. 56, n. 3, p. 208–211, 1985. Disponível em: https://pubmed.ncbi.nlm.nih.gov/3985899/. Access on: 12 Jun. 2025.

YOKOTA, M.; KARIS, A. J.; THARION, W. J. Thermal-work strain in law enforcement personnel during chemical, biological, radiological, and nuclear (CBRN) training. **International Journal of Occupational and Environmental Health**, v. 20, n. 2, p. 126–133, 2014. Disponível em: https://pmc.ncbi.nlm.nih.gov/articles/PMC4060587/. Access on: 29 Jun. 2025.