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Indian Journal of Aerospace Medicine

Original Article

Changes in metabolic gas kinetics on exposure to heat stress

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Received : 28 February 2022
Accepted : 30 April 2022
Published : 21 October 2022

DOI
10.25259/IJASM_15_2022

Quick Response Code:

ABSTRACT

Objectives: Heat stress is one of the major stressors in military aviation with the potential to adversely affect the efficiency of the aircrew and hence flight safety. Metabolic rate (MR) increases on exposure to heat and metabolic gases are considered as a proxy for MR. This study examined the influence of heat stress on metabolic gas kinetics in healthy Indian males and assessed the duration of attaining normal baseline values of metabolic gases post-exposure.

Materials and Methods: In 16 healthy male volunteers, cardiorespiratory variables, including metabolic gases (oxygen uptake [VO_2], carbon dioxide output [VCO_2], minute ventilation [V_E], breathing frequency [BF], and heart rate [HR]), were recorded before and approximately 2 h after a standard meal. The subjects were then exposed to a simulated temperature of 40°C with a relative humidity of 70% for 1 h in the environmental chamber. Same physiological parameters were recorded at the end of 30 min and 60 min during heat exposure and up to 90 min following exposure to heat stress at an interval of 30 min.

Results: A significant increase ($P < 0.001$) in mean VO_2 (ml/Kg/min) was observed post-meal (1.49 ± 0.95) as well as at 30 min (1.17 ± 0.96) and at 60 min (2.14 ± 1.19) of heat exposure. A similar increase ($P < 0.05$) in mean VCO_2 was observed post-meal and following heat exposure. V_E (L/min) increased by 12.12% post-meal ($P = 0.01$), 16.16% ($P < 0.001$) at 30 min, and 19.65% ($P < 0.001$) at 60 min of heat exposure. There was a significant increase in mean BF (per min) during heat exposure (2.31 ± 1.24 at 30 min and 3.53 ± 1.05 at 60 min) and till 60 min of the recovery period compared to baseline ($P < 0.001$). HR (bpm) increased by 14 bpm at 30 min and 17 bpm at 60 min of exposure and till 30 min after elimination of heat stress ($P < 0.001$).

Conclusion: A statistically significant increase was observed in VO_2, VCO_2, V_E, BF, and HR on exposure to heat stress. Optimal recovery was observed after 30 min of eliminating the heat stress for VO_2 and VCO_2. Similar recovery was observed after 60 min of eliminating the heat stress for HR and following 90 min for V_E and BF. Hence, if the crew is required to continue to operate in the heat stress environment, a minimum period of 90 min of a break in between the sorties must be ensured in a relatively cooler environment.

Keywords: Heat stress, VO_2, VCO_2, V_E, Breathing frequency, Heart rate

INTRODUCTION

Temperature variations have a significant impact on living organisms in tropical countries. In humans, ambient temperature primarily affects the core body temperature (T_c) and thus metabolic rate (MR). These changes in T_c and MR have a detrimental effect on the physical and mental performance of the individual. Similarly, military aviators who invariably get exposed to extremes of temperatures are prone to experience impairment of their ability to perform a task

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in the cockpit.[1] This may have a critical effect on flight safety and mission accomplishment. Significant effects of heat stress are seen among aviators, especially during high-speed low-level flying, where the cockpit temperatures could exceed 40°C.[2-4] Any physical activity of an individual will increase the level of heat production and accounts for the total energy expenditure.[1] Replenishment of these energy stores occurs during the recovery period or the post-exposure period. Various cardiological and respiratory changes, namely, increase in heart rate (HR), increased sweat rate, and increase in oxygen uptake (VO_2), occur due to heat stress.[5] Body generally takes anywhere from 15 min to 48 h to fully recover to a resting state. The duration of recovery or replenishment of the energy stores not only depends on the duration of exposure to stress but is also directly proportional to the intensity of stress and physical activity after eliminating the stressor.[6]

In military aviation, aircrew may be required to undertake multiple or long-haul sorties causing prolonged exposure to heat and thus making them vulnerable to the effects of heat stress. Heat stress causes an increase in MR expressed in terms of metabolic gas kinetics (VO_2 and carbon dioxide elimination). It is necessary to restore the expended energy with adequate rest before any further physical activity or exposure to stressors to prevent exhaustion. Hence, with a hypothesis that a significant increase in metabolic gas kinetics occurs on exposure to heat stress, this study was conducted to assess the changes and the duration required for the optimal recovery of cardiorespiratory variables such as VO_2, carbon dioxide elimination (VCO_2), minute ventilation (V_E), breathing frequency (BF), and HR.

MATERIALS AND METHODS

Subjects

A total of 16 randomly selected healthy male volunteers (age – 31.1 ± 4.8 years, height – 174.5 ± 7 cm, and weight – 76.4 ± 9.2 kg) participated in this study. Participants were screened and evaluated for their medical fitness to undergo the study protocol. The protocol was approved by the Institute Ethics Committee and written informed consent was obtained from the volunteers.

Equipment

The multi-seated environmental chamber installed at the Department of Environmental Physiology, Institute of Aerospace Medicine, Bengaluru, was used for simulating the desired thermal condition (temperature of 40°C with a relative humidity of 70%) for this study. CPET equipment (VO_2 max^{Tracker} Ergospirometer manufactured by M/s MES®, Poland) capable of analyzing the changes in metabolic gas kinetics was used for recording cardiorespiratory variables (VO_2, VCO_2, V_E, BF, and HR). A single-piece durable, air permeable, lightweight, and flame retardant flying overall, same as that used by the pilots in IAF were worn by all the participants for this study. Participants also donned Aerazur-EFA-F6101 Anti-G suit.

Protocol

Participants were advised to abstain from consuming tea or beverages containing theobromine or caffeine for 12 h before the study, avoid exercise for 24 h, and maintain strict abstinence from alcohol from 3 days before the study. Anthropometric parameters such as height, weight, and body mass index were recorded on arrival. Cardiopulmonary exercise testing parameters such as VO_2, VCO_2, V_E, BF, and HR were recorded on empty stomach for baseline readings with CPET equipment. Standard breakfast with adequate hydration was provided to all subjects to maintain homogeneity of the thermogenic effect of food. Post-meal readings of the same parameters were recorded after a period of approximately 2 h (just before exposing the subjects to heat stress). Participants were then seated in the multi-seated human-environmental chamber at a temperature of 40°C with a relative humidity of 70% for 60 min. During exposure, two readings, one at the end of 30 min of exposure and another at the end of 60 min of exposure, were recorded. Post-exposure, the same parameters were recorded at the end of 30 min, 60 min, and 90 min in the recovery room with an ambient temperature maintained at 23°C. All recordings of parameters both inside and outside the environmental chamber were recorded in a sitting position for an average duration of 15 min. The test was terminated on completion of the procedure or when the subject felt uncomfortable and wished to stop the protocol/remove the mask.

Statistical analysis

Repeated measures analysis of variance was used to find out the changes in the physiological parameters VO_2, VCO_2, V_E, BF, and HR between baseline, post-meal, during exposure to heat stress, and during the recovery period at 30 min, 60 min, and 90 min (post-exposure). The level of significance was kept at $P < 0.05$. The pair-wise comparison was performed using either Tukey's or Wilcoxon *post hoc* analysis.

RESULTS

Mean values of cardiorespiratory and physiological parameters (VO_2, VCO_2, V_E, BF, and HR) at different conditions are mentioned in [Table 1].

VO_2 showed significant changes on exposure to heat stress/different conditions with $F(6, 90) = 22.52$ and $P < 0.001$. *Post hoc* analysis revealed that VO_2 was significantly higher post-meal and on exposure to a hot environment compared to baseline and post-exposure values [Table 2].

VCO_2 showed significant changes on exposure to heat stress/different conditions with F (6, 90) = 7.228 (P < 0.001). Levene's test for homogeneity was found to be significant (P = 0.029). Hence, Wilcoxon *post hoc* analysis was carried out. Similar to VO_2, *post hoc* analysis revealed that VCO_2 was also significantly higher during post-meal and on exposure to a hot environment compared to baseline and post-exposure values. VCO_2 reached below the baseline in 30 min of post-exposure and increased to near baseline in the next 1 h of recovery [Table 3].

BF showed significant changes on exposure to heat stress/different conditions with F (6, 90) = 30.24 (P < 0.001). *Post hoc* analysis revealed that the increase in BF on exposure to heat was significant throughout the duration of exposure and till 1 h of the post-exposure recovery period when compared to the baseline recordings [Table 4].

VE showed significant changes on exposure to heat stress/different conditions with F (6, 90) = 7.342 and P < 0.001. *Post hoc* analysis revealed that VE was significantly higher during post-meal, exposure to a hot environment, and till 1 h of post-exposure recovery period when compared to the baseline value [Table 5].

HR showed significant changes on exposure to heat stress/different conditions with F (6, 90) = 58.26 and P < 0.001. *Post hoc* analysis revealed that HR was significantly higher during exposure to a hot environment and till 30 min of the post-exposure recovery period when compared to the baseline recordings [Table 6].

DISCUSSION

Heat stress has already been a recognized physiological threat among military aviators. It is also a known fact that heat stress

Table 1: Mean values of the measured physiological parameters at different phases.

Phase	Baseline	Post-meal	30 min in TC (TC-1)	60 min in TC (TC-2)	PE-30	PE-60	PE-90
VO_2 (ml/Kg/min)	4.70±0.80	6.19±1.09	5.87±0.88	6.84±1.10	4.80±0.87	4.81±0.91	4.91±0.75
VCO_2 (ml/Kg/min)	0.29±0.04	0.35±0.03	0.31±0.03	0.32±0.03	0.28±0.03	0.29±0.06	0.30±0.05
V_E (L/min)	9.77±1.85	10.87±1.78	11.33±2.13	11.63±2.19	10.94±1.95	10.81±1.42	10.31±1.53
BF (per min)	18.11±2.50	18.53±2.69	20.41±2.35	21.63±1.97	20.09±2.55	19.55±2.60	18.54±2.26
HR (bpm)	73.18±8.44	76.14±8.77	83.57±9.23	90.25±10.22	78.96±9.63	75.19±9.80	73.12±9.72

TC: Thermal chamber during heat exposure, PE: Post-exposure to heat stress

Table 2: Pair-wise comparison of oxygen consumption rate using Tukey's *post hoc* analysis.

	Oxygen consumption rate (VO_2)						
	Baseline	**Post-meal**	**TC-1**	**TC-2**	**PE-30**	**PE-60**	**PE-90**
Baseline		1.39E-06*	0.000264*	4.45E-10*	0.9996	0.9994	0.9798
Post-meal	1.39E-06		0.8601	0.1482	7.83E-06	9.15E-06	4.74E-05
TC-1	0.000264	0.8601		0.004054	0.00118	0.001348	0.005314
TC-2	4.45E-10	0.1482	0.004054		5.03E-10	5.16E-10	9.68E-10
PE-30	0.9996	7.83E-06	0.00118	5.03E-10		1	0.9994
PE-60	0.9994	9.15E-06	0.001348	5.16E-10	1		0.9997
PE-90	0.9798	4.74E-05	0.005314	9.68E-10	0.9994	0.9997	

*P<0.05

Table 3: Pair-wise comparison of carbon dioxide eliminated using Wilcoxon *post hoc* analysis.

	Carbon dioxide eliminated (VCO_2)						
	Baseline	**Post-meal**	**TC-1**	**TC-2**	**PE-30**	**PE-60**	**PE-90**
Baseline		0.000443*	0.04288*	0.003479*	0.4458	0.8888	0.5518
Post-meal	0.000443		0.00177	0.01337	0.000229	0.005997	0.002228
TC-1	0.04288	0.00177		0.3302	0.02183	0.2343	0.197
TC-2	0.003479	0.01337	0.3302		0.01024	0.0704	0.08005
PE-30	0.4458	0.000229	0.02183	0.01024		0.3683	0.2306
PE-60	0.8888	0.005997	0.2343	0.0704	0.3683		0.8528
PE-90	0.5518	0.002228	0.197	0.08005	0.2306	0.8528	

*P<0.05

Table 4: Pair-wise comparison of breathing frequency using Tukey's *post hoc* analysis.

	Breathing frequency (BF)						
	Baseline	**Post-meal**	**TC-1**	**TC-2**	**PE-30**	**PE-60**	**PE-90**
Baseline		0.8412	5.77E-09*	4.35E-10*	5.00E-07*	0.000457*	0.8366
Post-meal	0.8412		2.01E-06	4.35E-10	0.000125	0.0355	1
TC-1	5.77E-09	2.01E-06		0.005221	0.9525	0.1214	2.09E-06
TC-2	4.35E-10	4.35E-10	0.005221		0.000139	1.26E-07	4.35E-10
PE-30	5.00E-07	0.000125	0.9525	0.000139		0.6461	0.00013
PE-60	0.000457	0.0355	0.1214	1.26E-07	0.6461		0.03646
PE-90	0.8366	1	2.09E-06	4.35E-10	0.00013	0.03646	

*P<0.05

Table 5: Pair-wise comparison of minute ventilation using Tukey's *post hoc* analysis.

	Minute ventilation (V_E)						
	Baseline	**Post-meal**	**TC-1**	**TC-2**	**PE-30**	**PE-60**	**PE-90**
Baseline		0.01716*	0.000113*	2.30E-06*	0.008883*	0.02813*	0.6378
Post-meal	0.01716		0.7825	0.2213	1	1	0.6021
TC-1	0.000113	0.7825		0.9645	0.8848	0.6816	0.03407
TC-2	2.30E-06	0.2213	0.9645		0.3265	0.1564	0.001703
PE-30	0.008883	1	0.8848	0.3265		0.9997	0.4617
PE-60	0.02813	1	0.6816	0.1564	0.9997		0.7108
PE-90	0.6378	0.6021	0.03407	0.001703	0.4617	0.7108	

*P<0.05

Table 6: Pair-wise comparison of heart rate using Tukey's *post hoc* analysis.

	Heart rate (HR)						
	Baseline	**Post-meal**	**TC-1**	**TC-2**	**PE-30**	**PE-60**	**PE-90**
Baseline		0.1581	4.37E-10*	4.35E-10*	6.80E-05*	0.6	1
Post-meal	0.1581		1.61E-07	4.35E-10	0.2047	0.9832	0.1419
TC-1	4.37E-10	1.61E-07		2.73E-06	0.002774	4.36E-09	4.36E-10
TC-2	4.35E-10	4.35E-10	2.73E-06		4.35E-10	4.35E-10	4.35E-10
PE-30	6.80E-05	0.2047	0.002774	4.35E-10		0.02797	5.58E-05
PE-60	0.6	0.9832	4.36E-09	4.35E-10	0.02797		0.5673
PE-90	1	0.1419	4.36E-10	4.35E-10	5.58E-05	0.5673	

*P<0.05

influences the performance of the aircrew during flying. In modern warfare, where "low-level high-speed flying" is required, there is an imminent risk of heat stress to aircrew. Of the numerous physiological responses that occur in the body on exposure to heat, cardiorespiratory variables such as VO_2, VCO_2, V_E, BF, and HR are considered to have an impact on the physical and mental abilities of the aircrew. This study was conducted with an aim to study such changes in the form of the metabolic gas kinetics on exposure to heat stress. VO_2 and VCO_2 are considered primary parameters and V_E, BF, and HR are considered secondary parameters in this study. In the past, studies had revealed that the cardiorespiratory variables vary with the ambient temperature and the energy expenditure depends on the intensity and duration of exposure to heat stress.[6] This study was undertaken to assess the effects of heat stress on various gas kinetic parameters to understand the duration of optimal performance of the individual in hot conditions and the time required for the replenishment of energy expended post-exposure.

VO_2 is considered and calculated as a proxy for MR.[5] MR increases post-meal and the end product of it is heat. Studies in the past reported that the increase in MR was due to the thermic effect of food.[7-11] Similar findings were also observed in this study. The increase in VO_2 post-meal was 1.49 ± 0.95 ml/Kg/min compared to baseline. Thus, the percentage of post-meal increase in VO_2 was 33.13% ($p < 0.001$). Similarly, a statistically significant increase of VO_2 of 27.02% was observed after 30 min of exposure to heat while 48.35% increase was recorded at the end of 1 h of heat exposure. Such a rise in VO_2 on exposure to heat stress was also documented by National Research Council (USA) in a laboratory study of VO_2.[12] This increase may be attributed to increased energy requirement to replenish the oxygen debt caused due to heat stress.[6,13,14] During the post-exposure period, the recovery was measured in the form of a percentage of approximation to the baseline value. Approximation levels of mean VO_2 to the baseline were found to be 95.98% at the end of 30 min and 96.77% at the end of 60 min depicting the level of recovery. Interestingly, there was a reinclination of VO_2 away from baseline from 96.77% at the end of 60 min to 94.59% at the end of 90 min of post-exposure.

An increase in VO_2 increases the gaseous exchange at the cellular level increasing carbon dioxide output (VCO_2). The mean difference in the amount of VCO_2 post-meal was 23.43% higher than the baseline. Furthermore, a significant increase of 8.54% at the end of 30 min of heat exposure and 12.41% at the end of 60 min of heat exposure was observed. During the recovery period, a significant decline was observed wherein the levels reached below the baseline (−2.75%) within 30 min of post-exposure (indicating 100% recovery). This finding of a rise in VCO_2 may be attributed to excess post-exposure oxygen consumption, leading to increased VCO_2.[14]

The increase in BF post-meal was not statistically significant. BF continued to increase significantly throughout heat exposure. The increase was of the magnitude of 13.36% at the end of 30 min and 20.37% at the end of 60 min of exposure. During recovery, BF remained statistically higher than the baseline at the end of 30 min and 60 min of post-exposure to heat stress. BF at 90 min of post-exposure was insignificant depicting optimal recovery ($P > 0.05$). These findings were in contrast to a study conducted by Raulph *et al.* (2012), where the respiratory rate remained constant throughout the exposure period.[15]

A 12.12% significant increase in V_E was observed post-meal. Similarly, V_E was also found to be significantly higher during 30 min and 60 min of heat exposure. Like BF, V_E values also did not reach the baseline values even after 60 min of the recovery period. However, the value at 90 min post-exposure was insignificant ($P = 0.63$) depicting an optimal recovery of V_E. Gaudio Raulph who conducted a study on heat-induced hyperventilation and had also observed an increase in V_E though not statistically significant. Consolazio *et al.*[16] and Henderson *et al.*[5] had also reported similar findings in the past. The increase in V_E has been related to increase in tidal volume during heat exposure.[15]

No significant increase in HR was observed post-meal. However, HR increased by 10 bpm (14.46%) and 17 bpm (23.71%) on exposure to heat stress for 30 min and 60 min, respectively. This increase was statistically significant. Post-exposure, approximation of HR to baseline (a sign of recovery) was 92.05% and 97.27% after 30 min and 60 min of elimination of heat exposure, respectively. In comparison to baseline, the HR measured at the end of 30 min of the recovery period was statistically significant whereas, at 60 min post-exposure, there was no significant difference. Hence, it can be stated that optimal recovery of HR occurred at about 60 min of the recovery period. The findings of changes in HR observed in this study were similar to various studies in the past.[5,16-19]

CONCLUSION

Our study brings out a few important findings; that have relevance to aviation operations. The cardiorespiratory parameters were found to be significantly affected by exposure to heat stress. It was also observed that most of the parameters returned to baseline values in about 60 min post-exposure indicating recovery of the physiological functions. Hence, it is recommended that a minimum of 90 min of recovery time must be followed by the crew before undertaking any sensitive task following exposure to similar heat stress conditions. Furthermore, if the crew is required to continue to operate in the heat stress environment, a minimum period of 90 min of a break in between the sorties must be ensured in a relatively cooler environment.

Declaration of patient consent

Patient's consent not required as there are no patients in this study.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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How to cite this article: Parwath SR, Mohapatra SS, Malhotra VK. Changes in metabolic gas kinetics on exposure to heat stress. Indian J Aerosp Med 2022;66:9-14.