Range, Energy, and Heat of Motion in an NBC Anti-G Anthropomorphic Tank Suit

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The nuclear, biologic pathogen, chemical (NBC) anthropomorphic tank suit (ATS), designed by one of the authors, de Gaston, provided a protective liner of water against the skin to the neck. Range of motion was lost in 29 of 32 tests by 25% dry (without) and 30% wet (with water in the liner), $P<0.001$. For exercise of 48–149 W, body temperature was elevated, $P<0.05$, metabolic rate dry was 1.48 times higher than unclad and wet 1.73 times higher, $P<0.01$ (cf. 1.66 to 3.96, respectively, for space suits). The factors dry and wet, respectively, for heart rate were 1.2, 1.3; for systolic blood pressure 1.3, 1.4, $P<0.01$; for diastolic blood pressure 1.3, 1.4; for estimated mean blood pressure 1.3, 1.4, $P<0.02$; and for ventilation 1.3, 1.8, $P<0.02$. High blood pressures and core temperatures, with thermal "after-rise," suggested redesign. Vision narrowed at $+3.5$ G_z in the ATS dry but not at $+7.0$ G_z for 1.5 min in the ATS wet. Maximum G tolerance in the ATS wet remains unknown.

Introduction

THE introduction of nuclear, biologic pathogen, or chemical (NBC) agents into the mission environment threaten safety and limit human performance. A countermeasure is the NBC suit. Some of the consequences of performing in NBC suits are that ranges of motion are diminished, the metabolic costs of movements are increased, and heat accumulates. These consequences may limit mission performance and threaten safety at a secondary level. The task of this exploratory study was to test an NBC anthropomorphic tank suit (ATS) to determine how much mobility, thermoregulation, and efficiency of movement would be lost. The ATS was designed by one of the authors, de Gaston, and provided a protective liner of water in contact with the subject to the neck. The null hypothesis was that there would be found no significant differences among the unclad, clad dry (no water in the liner), and clad wet (with water in the liner) conditions for mobility, thermoregulation, energy cost, and cardiorespiratory responses to moderate work rates.

In 1944, the U.S. Army Air Force issued the G-3A anti-G suit and, in 1981, the U.S. Air Force issued the CSU 3-B/P anti-G suit, both operating with air bladders, yielding some practicality and, until recently, the necessary anti-G protection.[13] Presently, "G-inhibiter" systems have been installed in military aircraft to limit performance to a maximum of 9 G.[28] This suggested the need to extend the G-envelope of the crew to that of the aircraft. Another purpose of this study was to investigate the practical and the anti-G characteristics of the ATS.

The literature on NBC suits suggested that moderate ambient heating was sufficient to induce severe thermal stress in pilots.[5] Thermal stress was found to increase significantly response times to all signals.[10] The physical characteristics of NBC suits, aside from thermal considerations, were responsible for the significant degradation of performances requiring fine eye-hand coordination.[29] These reports suggested that the induced thermal stress from an NBC suit was a significant threat to safety and performance.

The French may have used water in bladders as an anti-G suit as early as World War I.[35] In 1934, German scientists tested a G-suit lined with water from feet to neck that apparently fulfilled anti-G requirements but failed on practicality.[8] In the early 1940s, the Canadians tested in combat the water-lined Franks flying suit that apparently passed anti-G requirements but also failed on practicality.[13] Successful tests on humans in water capsules to 31 G_x (the limit of the centrifuge) and on rodents to 1300 G suggested the possibility of high gravity protection from water immersion.[8] The major problems involved practicality.[13,35]

Air or water may be used to remove heat from a working subject in an impermeable suit.[30] The method of choice for space suits was automatic water cooling.[31] This was confirmed in more than two hours of physical activity in a space suit, utilizing a water-cooled undergarment, on the lunar surface.[3]

The authors were unable to find reports on the energy requirements for work in NBC or anti-G suits and so sought instead reports on space suits. For exercise of about 150 W in Earth gravity and 1 atm, the metabolic cost of an unpressurized space suit was 1.66 times that of light clothing. For air pressurizations of 180 and 258 mm Hg, the factors were 2.93 and 3.90, respectively.[12,32] For similar conditions with 180 mm Hg pressurization, a factor of 3.11 was found.[9] For two different space suits pressurized to about 180 mm Hg, factors of 2.14 and 3.96 were found.[24] Subsequently with one of the suits modified, the factors were 2.31 and 3.47, respectively.[36] Compared to light clothing, these reports suggested that the unpressurized space suit raised energy requirements 1.66 times that of light clothing, and the suit pressurized with air from 2.14 to 3.96.

For a standardized task independent of body weight, like bicycle ergometry, the authors were unable to find for NBC or anti-G or space suits cardiorespiratory responses like heart rate, blood pressures, and expired volume. The authors also were unable to find for any of the suits any documentation on the losses of range of motion or any effects of being immersed to the neck, as in a tank suit. Therefore, another purpose of

Received April 14, 1990; revision received Nov. 16, 1990; accepted for publication Dec. 5, 1990.

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the study was to develop these protocols and to report these data on a small sample of men.

Methods

The subjects were three investigators for this study who gave their informed consent. The fourth investigator, a physician, took medical responsibility. Determinations were obtained on the three subjects unclad, as the standard, and were compared to the determinations in the ATS without water in the liner (dry), then with water in the liner (wet). The ATS results were reported as multiples or percentages of this unclad standard.

Range of motion was determined with a goniometer in a standardized protocol of 32 tests modified from the International SFTR Method by the American Academy of Orthopedic Surgeons.[6] There were 4 tests for the head and neck, 3 for the thoracic and lumbar spine, 8 for the leg, 6 for the hand, and 11 for the arm. The extreme positions of the motion, in degrees, were obtained with the goniometer, and the difference gave the range of motion. For the ATS dry and wet, these ranges of motion were normalized to the unclad determinations.

Energy requirements were determined by obtaining the oxygen consumption in a steady state on a Monarch bicycle ergometer, equipped with a pedal counter and speedometer, at a cycling rate of 50 rpm. Oxygen consumption was determined directly every 15 s with an open system, a modified Ametek OCM-1 Oxygen Uptake System, and was reported standard temperature (0°C) pressure (760 mm Hg) dry (0 mm Hg water vapor pressure) (STPD).[15] To obtain steady states, determinations were made for 6 min at 50 and 100 W, 5 min at 150 W, 4 min at 200 W, and 3 min at 250 W or higher.[2,17] The means of the last minute of exercise were used for comparisons. Blood pressures were obtained phonoarteriographically from an electronically recorded sphygmomanometric method intra-arterially validated for rest, exercise, and the rest after exercise.[14] Mean blood pressure was estimated as the diastolic blood pressure plus one-third of the pulse pressure. Heart rates were the mean of 10 R-to-R determinations obtained either from the electrocardiogram or the brachial pulse of the blood pressure tracings from a Statham SM1051 recorder. Expired volume was obtained from a Collins 120-l spirometer and was reported BTPS, body temperature (37°C) pressure (760 mm Hg) saturated (47 mm Hg water vapor pressure).

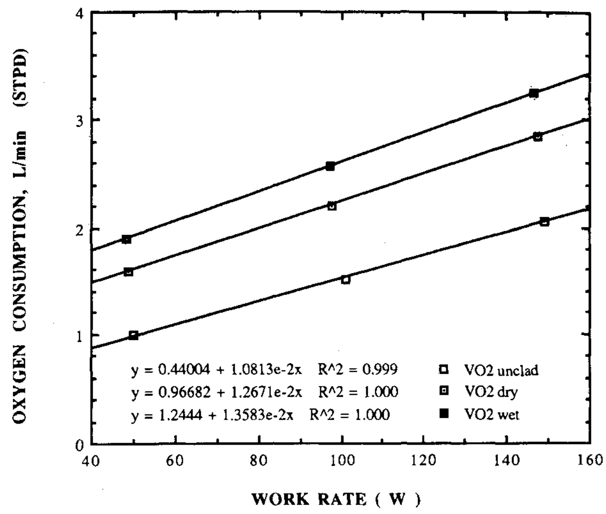

Fig. 3 Steady-state energy cost of cycling on a bicycle ergometer at 50 rpm unclad, in the ATS (dry) and in the ATS (wet, i.e., with 9.85 l of water in the liner) for the three subjects.

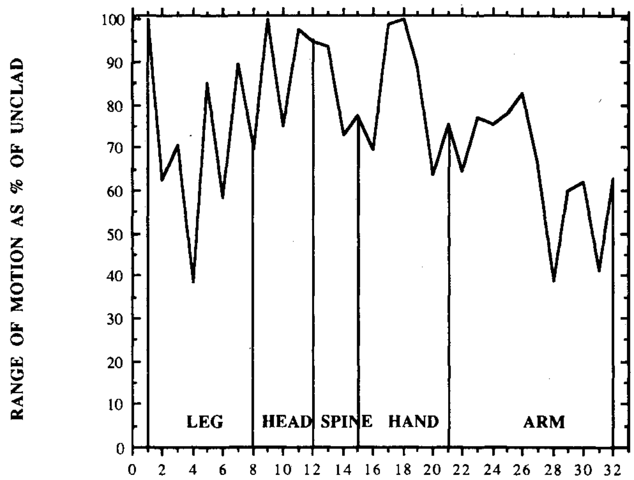

Fig. 1 Range of motion in the ATS (dry, i.e., without water in the liner) for the three subjects normalized to range of motion unclad. The abscissa represents the standardized protocol of 32 tests (see Methods and Ref. 6).

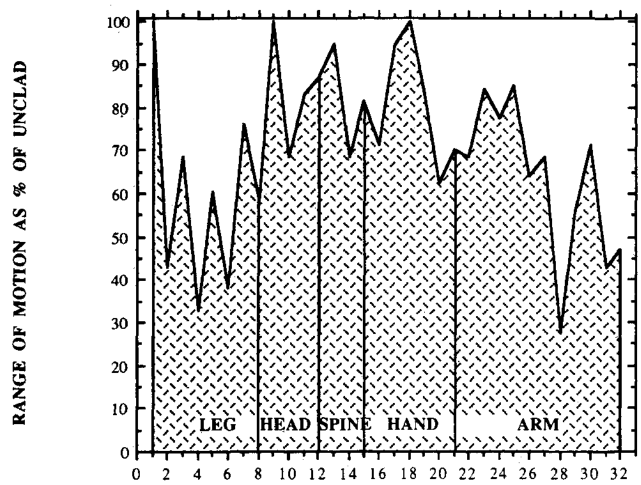

Fig. 2 Range of motion in the ATS (wet, i.e., with 12.4 l of water in the liner) for the three subjects normalized to range of motion unclad. The abscissa represents the standardized protocol of 32 tests (see Methods and Ref. 6).

Rectal temperature in degrees Celsius was obtained with a thermistor probe inserted 8 in. (20 cm) into the rectum[18-23] and a Yellow Springs Instruments Tele-Thermometer meter. Determinations were made for each minute of exercise and rest unclad, in the ATS dry and in the ATS wet. Temperature determinations also were made on the water used to fill the liner. Humidity was determined with a sling psychrometer, and barometric pressure was obtained from an airport weather station within 11 miles (17.7 km) of the laboratory.

Except for progressive donning experiments, unclad determinations were made in one session and the clad, dry then wet, determinations were made in a second session on a separate day. If a steady state was obtainable dry, then the assumption was made that the subsequent wet determinations were unaffected, as is the case in discontinuous and continuous exercise tests.[2,16,17] Time in the suit and the quantity, as well as the temperature, of the water put in the liner were recorded. Body and suit weights were obtained on a balance with a range of 153 kg that was sensitive and accurate to 5 *g*.

All three subjects completed all of the range of motion and exercise protocols unclad, dry, and wet (Figs. 1–6). Economic, certification, and time constraints limited the centrifuge testing to subject 1 and to one test in the ATS dry and wet. Only subject 3 was progressively clad and exercised dry (Figs. 7 and 8). Only subjects 2 and 3 progressively donned the ATS sleeve (Fig. 9).

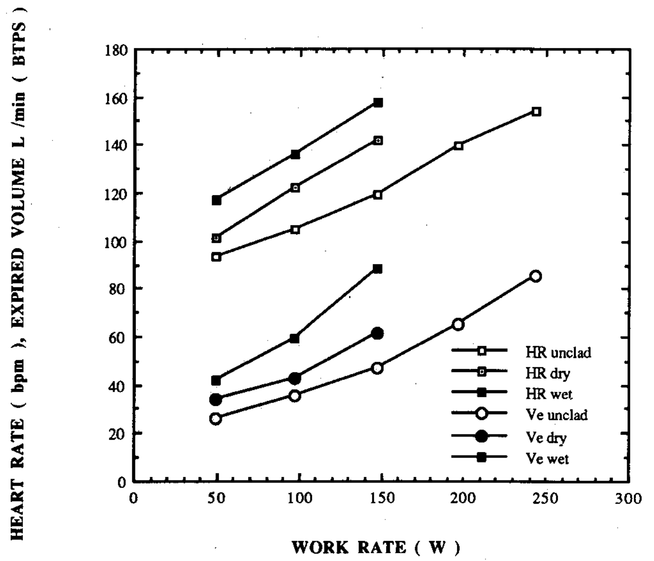

Fig. 4 Steady-state heart rate (HR) and expired volume (Ve) of cycling on a bicycle ergometer at 50 rpm unclad, in the ATS (dry) and in the ATS (wet, i.e., with 9.85 l of water in the liner) for the three subjects.

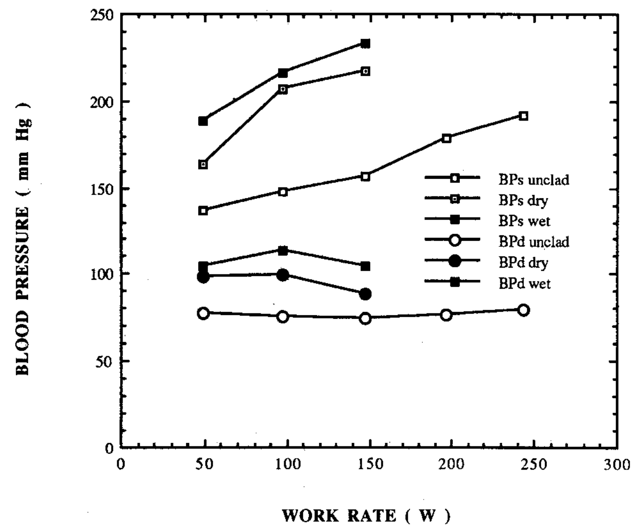

Fig. 5 Steady-state phonoarteriograghic systolic (BPs) and diastolic (BPd) blood pressures of cycling on a bicycle ergometer at 50 rpm unclad, in the ATS (dry) and in the ATS (wet, i.e., with 9.85 l of water in the liner) for the three subjects.

The differences among the means unclad, in the ATS dry and in the ATS wet, were tested with an analysis of variance ($df = 2, 2$), and $P < 0.05$ was considered statistically significant.

Results

The mean (± standard deviation) age of the subjects was 43.8 ± 15.1 yr, height was 185.1 ± 2.9 cm, and body weight was 82.8 ± 2.5 kg. All three subjects were in good physical condition. The lowest peak oxygen consumption of 4.02 l/min (50 ml/min kg) and the highest body fat content of 13% were for subject 2. The dry ATS weighed 5.6 kg, and the water in the liner varied from 9.85 to 12.4 kg, for a total weight of 15.45 (34.1 lb) to 18.0 kg (39.7 lb). Time in the ATS averaged 212 ± 23 min per session.

In the ATS, there was a loss in range of motion in 29 of the 32 movements tested, 14 of which were statistically significant: foot extension (test 2), foreleg flexion (test 3), femur flexion (test 4), femur extension (test 5), head extension (test 10), hand flexion (test 16), forearm flexion (test 22), horizontal humeral outward rotation (test 26), horizontal humeral abduction (test 27) and adduction (test 28), humeral flexion (test 29) and extension (test 30), and humeral abduction (test 31) and adduction (test 32). In percent, the mean (± SD) losses dry and wet, respectively, were 28.1 ± 7.6 and 40.2 ± 14.9 for the legs ($P = 0.002$), 8.1 ± 1.0 and 15.4 ± 2.4 for the head ($P = 0.06$), 18.6 ± 2.5 and 18.3 ± 2.9 for the thoracic and lumbar spine ($P < 0.04$), 17.2 ± 3.2 and 19.5 ± 3.6 for the hand ($P = 0.06$), 35.6 ± 7.9 and 37.0 ± 10.6 for the arm ($P < 0.001$), and overall 25.3 ± 5.9 and 30.1 ± 8.4 ($P < 0.001$), as may be seen in greater detail in Figs. 1 and 2. The water in the liner was 12.4 ± 0.1 l.

For the steady-state work rates from 48 to 149 W, normalizing the response for each watt of work rate, the ATS dry required a metabolic rate 1.48 times higher than unclad, and the ATS wet 1.73 times higher. Unclad, dry, and wet were significantly different from each other at each work rate, $P = 0.01$.

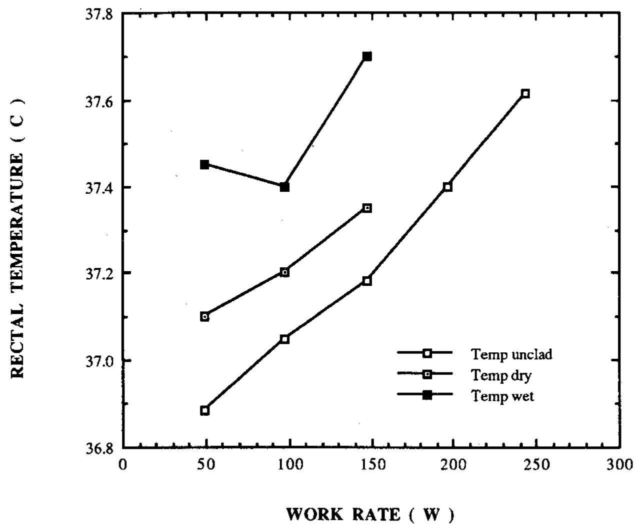

Fig. 6 Steady-state rectal temperature of cycling on a bicycle ergometer at 50 rpm unclad, in the ATS (dry) and in the ATS (wet, i.e., with 9.875 l of water in the liner) for the three subjects.

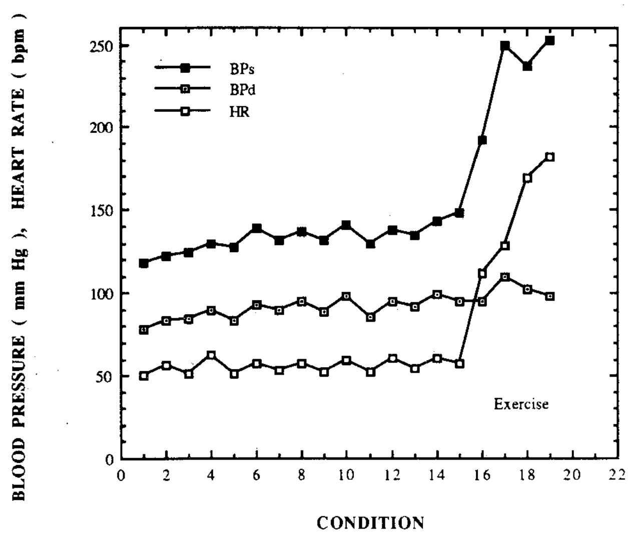

Fig. 7 Steady-state heart rate (HR) and phonoarteriograghic systolic (BPs) and diastolic (BPd) blood pressures, alternately sitting then standing, as the ATS (dry) was progressively donned and laced (conditions 1–14) for subject 3. Condition 15 was sitting quietly on the bicycle ergometer. For conditions 1–15, each data point was the mean of five determinations. Compared to seated, unclad, blood pressures were significantly higher, and all the standing heart rates and the last two seated (completely laced) were higher, $P < 0.001$. Conditions 16–19 were cycling at 50 rpm to a steady state at 50, 100, and 200 W, respectively.

The equations indicated increased slopes, as well as intercepts, with high accuracy of fit to the data, $R^2 = 0.999$ or 1.000, as may be seen in Fig. 3. The heart rate responses were higher by factors of 1.2 dry and 1.3 wet and those for ventilation 1.3 and 1.8, respectively, as may be seen in Fig. 4. Except for the heart rates at 48 W, the differences were statistically significant. The factors for both the systolic and the diastolic blood pressures were 1.3 and 1.4, respectively, as may be seen in Fig. 5. The differences were statistically significant for the systolic and estimated mean blood pressures, but not the diastolic blood pressures. Unclad, rectal temperature rose linearly with work rate. Clad, without water in the liner, the temperatures were elevated. Upon the addition of 9.85 ± 1.01 l of water, causing an overflow at the neck, at 23.65 ± 0.38°C, temperature continued to rise after a sign of small decline, as may be seen in Fig. 6. The differences were statistically significant. Total time in the ATS averaged 212 ± 23 min, time wet was 98 ± 18 min, and in that time the linear water temperature rose to 34.17 ± 0.98°C as the subject dehydrated 1.55 ± 0.65 l (about 1.9% of the body weight). The room temperature averaged 25.5 ± 0.8°, with 59 ± 4.6% humidity.

On subject 3, five determinations were obtained, alternately sitting then standing, while progressing from unclad (condition 1 sitting, condition 2 standing) to completely clad and laced, dry in the ATS, condition 13 sitting and 14 standing. The subject then sat quietly on the bicycle ergometer, condition 15. The subject then exercised at 50, 100, 150, and 200 W as conditions 16, 17, 18, and 19, respectively. The rest after exercise was observed for body temperature only at minutes 20 and 66, conditions 20 and 21, respectively. The subject was in a thermal steady state from condition 7 (laced four eyelets above the waist) through 15, a period of 73 min, as may be seen in Fig. 8. The specific rise with standing and the fall with sitting of the heart rate and the blood pressures were discernable, as were the general rise with donning and the progressive lacing of the suit. Compared to condition 1 (resting, seated, unclad), all donned conditions were statistically significantly higher for systolic and diastolic blood pressures, $P < 0.001$. During exercise, systolic blood pressures of 250 and 253 mm Hg and diastolic blood pressures of 110 and 102 were observed, as may be seen in Fig. 7, and were unprecedented for this subject because unclad at 248 W his systolic blood pressure was 208 mm Hg and his diastolic blood pressure was 76 mm Hg. Only the seated heart rates while completely laced in the suit, conditions 13 and 15, and all of the standing heart rates were significantly higher, $P < 0.001$. Rectal temperature was stable during rest for 73 min, rose during exercise and for 22 min after exercise, 4 min of which were in the doffed condition, then required 46 min unclad to return to 37°C, as may be seen in Fig. 8.

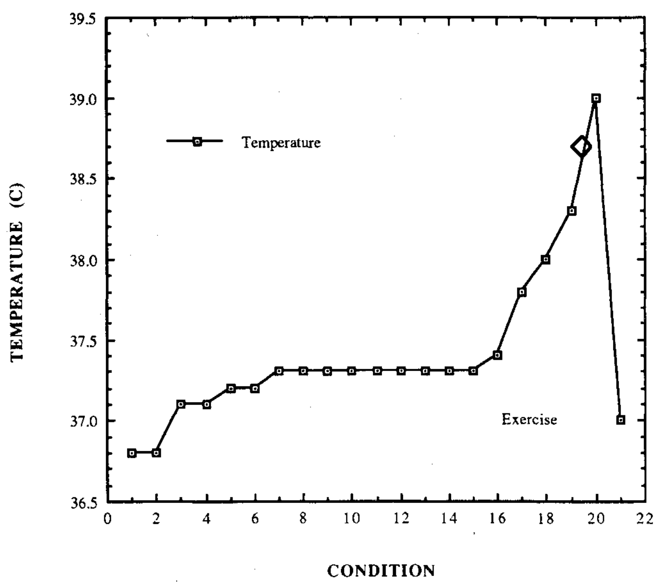

Fig. 8 Rectal temperature for subject 3, alternately sitting then standing, as the ATS (dry) was progressively donned and laced (conditions 1–14). Condition 15 was sitting quietly on the bicycle ergometer. For conditions 1–15, each data point was the mean of five determinations. Conditions 16–19 were cycling at 50 rpm to a steady state at 50, 100, 150, and 200 W, respectively. Exercise ceased at condition 19, and rectal temperature continued to rise for 22 min to condition 20 while seated at rest, and demonstrated the "after-rise" phenomenon. The ATS was doffed at the diamond symbol. From condition 20 to 21 seated at rest, 46 min were required for the return to 37°C.

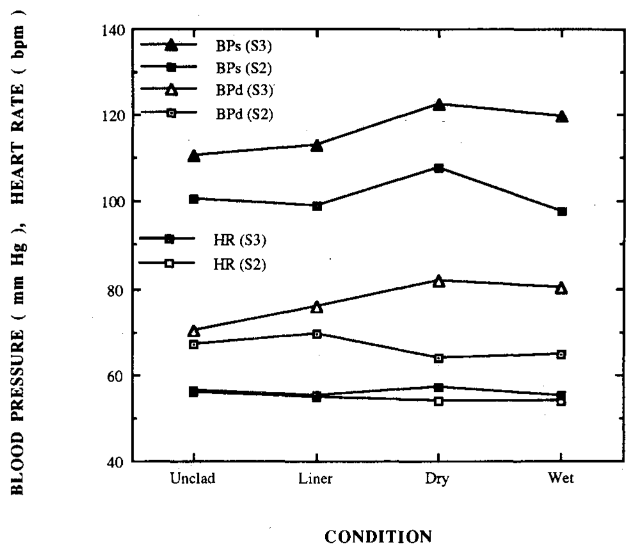

Fig. 9 Steady-state phonoarteriographic systolic (BPs) and diastolic (BPd) blood pressures for subjects 2 and 3 were determined seated and unclad. The blood pressure cuff was removed, then reapplied over the liner sleeve as only the liner sleeve was donned (liner). The process was repeated as the outer sleeve was put over the liner (dry). The blood pressure cuff remained in place as the sleeve's liner was filled with water (wet). Heart rates (HR) were obtained from the brachial pulse sound tracings. Determinations were obtained on subjects 2 and 3. Each data point was the mean of 10 determinations.

In an effort to determine whether the high blood pressures were artifacts, subjects 2 and 3 were observed sitting unclad, then with only the right arm in the liner, then with only the right arm completely clad and dry, and then finally with water added. The blood pressures seemed normal and did not seem to provide evidence of artifact, as may be seen in Fig. 9. The differences between unclad, liner, dry, and wet were not statistically significant, $P > 0.58$.

Subject 1 was selected for trials in a centrifuge. Clad in the ATS without water in the liner, in normal sitting posture, relaxed, and without any voluntary straining maneuvers, at $+3.5\ G_z$, vision narrowed and the test was stopped. Clad in the ATS with water in the liner, otherwise under the same conditions, $+7.0\ G_z$ for 1.5 min was attained without any untoward effects. (Vision did not narrow.) This test was stopped because the centrifuge was at its rated maximum and mechanically began to fail.

Discussion

Most of the loss in range of motion, 25%, was caused by the stiffness of the ATS. The addition of the water to the liner resulted in a modest additional overall 5% loss in mobility, as may be seen in Figs. 1 and 2. Similarly, most of the increased metabolic cost of motion may be attributed to the stiffness of the ATS, rather than to the water in the lining. The stiffness of the suit is represented in the metabolic rate equation by an increase in the intercept of 113% and by an increase in the slope of 17%. The average additional energy cost from the suit for the three work rates was 48%, and from the water an additional 25%, as may be seen in Fig. 3. If not limited by other factors, this suggested that the unclad work rate that elicited the maximal metabolic rate of physical activity would be attenuated clad dry and clad wet by the respective equations. Normalized per watt of work rate, nearly all of the increased cost of motion was reflected in the increased ventilations (VO_2 factors dry, wet = 1.48, 1.73; Ve factors = 1.28, 1.76), and about 80% in the increased heart rates (HR factors = 1.15, 1.29) and blood pressures (BPs factors = 1.33, 1.44; BPd factors = 1.26, 1.42), as may be seen in Figs. 4 and 5.

About 117 kcal were converted to heat in the first series of exercise bouts in the ATS dry, and about 137 kcal in the second series in the ATS wet, for a total of 254 kcal of heat above the resting metabolism. About 102 kcal were absorbed by the liner water, leaving a remainder of 152 kcal. This could have raised the estimated body water (50.6 l) 3.0°C and yielded an expected rectal temperature of 40.1°C, the upper extreme of the physiologic range. Yet, the highest temperature observed at the end of the last series of exercises, with the calibration of the thermometer doubly checked, was 37.7°C, as may be seen in Fig. 6. The experiment in Fig. 8 showed a steady resting state seated of 37.3°C for 73 min, suggesting that the dry ATS permitted the regulation of body temperature at rest seated. The pulse of heat from the exercises was calculated at 174 kcal to raise the body water of the subject (estimated at 50.7 l) to 40.7°C. At the end of exercise, temperature was observed at 38.3°C. Temperature continued to rise to 38.8°C at the time of doffing. Four min after doffing, temperature peaked at 39.0°C, in what may be dubbed an "after-rise" phenomenon, and thereafter fell to 37.0°C in 46 min in the unclad condition. This after-rise phenomenon may be analogous to the "afterdrop" found during rewarming after hypothermia. The mechanisms causing afterdrop may be simply conductive,[33] or coupled with some convective contribution from circulation.[5,18,25]

In air, heat from leg exercise raised rectal temperature more than esophageal temperature.[19] However, immersion of dogs has shown a redistribution of blood flow from gastrointestinal tissues toward skeletal muscle tissues (as well as a 32% increase in arterial pressure).[7] Immersion also may cause a cephalad shift in blood volume.[27] The data in the present study were consistent with the assumption that the calculated pulses of heat were in the subjects, but in large measure in the exercised muscles and the cephalad shifted blood, rather than in the tissues surrounding the rectum.

In air, passive heating from diathermy and active heating from exercise raised rectal temperature and skin blood flow to about the same level and suggested that the main stimulus for increased heat dissipation during a steady-state work rate was the increased internal temperature.[21] In treadmill experiments, rectal temperature and heat dissipation, from sweat rate and skin circulation, increased according to energy production, rather than total heat production or neuromuscular factors.[22,23] In the present study, there were both heat accumulation and energy production to increase cutaneous circulation and heat dissipation. During heavy exercise, with a subject immersed in cool water of various temperatures, his body's heat flow was constant, perhaps because of progressive cutaneous vasodilation.[5] However, with a subject in water at 35°C, his rectal temperature rose during exercise, requiring an O_2 consumption of 0.9 l/min.[12] Recently, critical water temperature was reported at 31.2°C.[26] In the present study, O_2 consumption was 2.39 ± 0.62 l/min, and final water temperature in the suit was 34.17 ± 0.98°C. These conditions militated significantly against any additional heat dissipation to the liner water.

When the ATS was doffed, the hydrostatic pressure was removed, blood flow probably shifted caudally, and from the muscles to the gut, where the thermistor sensed what remained of the bolus of heat. The data also suggested that a heat pulse equal to the heat absorbed by the liner water, i.e., 100 kcal in the present protocol, would be safe and physiologically manageable if the subject were permitted to re-establish the seated resting steady state. These experiences suggested that unmeasured heat loads may increase the risk of heat injury, even in monitored conditions, because of the after-rise phenomenon and the technical difficulties in detecting heat accumulation. The thermal after-rise, like afterdrop, should be targeted for investigation and management because of the significant threat to safety.

Mobility was significantly diminished. The energy cost of work, the cardiorespiratory and thermal responses, for the most part, were increased significantly. Therefore, the null hypothesis was rejected. For future studies, mobility may be improved by reducing the resistance to motion at selected joints. This also would reduce the energy cost of motion, as well as the other physiologic responses. Reduction of the hypertensive threat, additionally, may require restricting work rates. Reduction of the thermal threat, additionally, may require active cooling of the liner water. Taken together, these measures may provide a practical NBC garment.

The G-suits using air bladders for arterial occlusion with very rapid pressure control valves have been reported to give protection of 2.1–2.9 G — more than double the protection from the water-lined Franks suit.[34] The ATS of the present study was a preliminary design, and apparently offered protection to $+3.5\ G_z$ without water in the liner. With water in the liner, protection was at least $+7.0\ G_z$ for 1.5 min, the limit of the centrifuge before it began to fail. A description of the maximum capacity for gravity protection of the ATS must await testing in a centrifuge with a capacity greater than $+7.0\ G_z$.

Summary and Conclusions

The purpose of the study was to test range of motion, energy required to move, cardiorespiratory responses, and heat accumulation of an NBC water-lined anthropomorphic tank suit designed by de Gaston. Three subjects were tested in the ATS without (dry) and with (wet) water in the liner. The null hypothesis was that there would be found no significant differences among the unclad, dry, and wet conditions for mobility, thermoregulation, energy cost, and cardiorespiratory responses to moderate work rates. The results indicated a loss of range of motion in 29 of 32 tests by an average of 25% dry and 30% wet, $P < 0.001$. For steady-state work rates from 48 to 149 W, the ATS dry required a metabolic rate 1.48 times higher than unclad, and the ATS wet 1.73 times higher, $P < 0.01$. These increases in metabolic rate also were reflected in higher heart rates, blood pressures, ventilations, and rectal temperatures, most of which were statistically significant. Therefore, the null hypothesis was rejected.

The ATS permitted the regulation of body temperature in a seated resting steady state at 37.3°C. In the present configuration and protocol, a heat pulse of 100 kcal, equal to the heat absorption of the liner water, was found safe, with exposure times averaging 212 min. Thermal after-rise and hypertensive responses were identified as significant threats to safety in steady-state work rates to 150 W. Reduction of resistance to motion at selected joints, active cooling of the liner water, and restriction of work rates may minimize these threats and provide a practical NBC garment. The anti-G protection may be $+7.0\ G_z$ or greater.

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