Dry Bulb Temperature Effects on Crew Well-Being in Long-Duration Ad Hoc Platform Flights

Todd R. Fredricks; Masato Nakazawa

PURPOSE: U.S. combat activities in Iraq and Afghanistan saw the implementation of multiple ad hoc systems incorporated onto commercial aerial platforms for supporting operations. The use of manned platforms, many of which were never intended for the long-duration missions to which they have been applied, has had human factor and aviation life support equipment (ALSE) implications. The physiological stress-inducing nature of high temperatures (> 40 C) is one such concern. This study assessed cockpit temperatures in one such platform during actual combat missions over Iraq.

METHODS: Three missions were flown in Iraq during 2011 on an ad hoc aerial platform and dry bulb temperature readings were recorded periodically at head height at different crew stations. Relative humidity was also recorded.

RESULTS: Temperatures demonstrated wide variability during mission profiles, ranging from > 40°C to 15°C. Ground heat-soaked cabin temperatures were measured as high as 48°C. High temperatures could be experienced for up to an hour prior to departure.

DISCUSSION: While ad hoc aerial platform use has operational merits, the lack of adequate crew life support systems on such platforms can pose thermal risks to the aircrews. More detailed investigation is needed to determine core temperature response of aircrews during such operations and platform specific ALSE requirements to better support aircrew mission effectiveness.

KEYWORDS: U.S. Army, temperature, aircrew, fixed-wing, long-duration flight, ad hoc.

Fredricks TR, Nakazawa M. *Dry bulb temperature effects on crew well-being in long-duration ad hoc platform flights*. Aerosp Med Hum Perform. 2015; 86(2):125–130.

U.S. operations during Operations Enduring Freedom and Iraqi Freedom have driven the rapid implementation of new combat technologies. Among these have been various ad hoc aerial systems that have used commercial off-the-shelf (COTS) aircraft to facilitate rapid deployment. During the primary investigator's third tour of Iraq, while acting as a flight surgeon supporting the crews of COTS ad hoc aerial platforms, several different aircrew members remarked that they were purposely dehydrating themselves due to lack of toilet facilities on long-duration (> 4-h) missions. This willful activity among aircrew is of concern given the detrimental effects of dehydration on flight performance[13] and the known losses of body moisture from evaporative cooling in high ambient temperature (HAT) operating environments.[11,16] The general operations area of these crews was between Tikrit, Iraq, which has an ambient temperature on the ground above 40°C for over 2 mo of the year, and the Iraqi-Kuwaiti border, which remains above 40°C for up to 5 mo of the year.[12,17] The aircrew members spoke of frequent extended taxi times during periods of high operational tempo. The long taxi times resulted in exposure to excessive cabin heat as electronic systems were operating and their aircraft were unable to provide either adequate ventilation or mechanical environmental control while on the ground pending departure.

Froom et al. documented a linear relationship noted in cockpit heat stress experienced by aircrews during long ground wait times.[6] Breckenridge and Levell quantified cockpit greenhouse heating effects on the ground in HAT and noted the inability of their model to maintain optimal core temperature (< 40°C)

From the Ohio University Heritage College of Osteopathic Medicine, Ohio University, Athens, OH.

This manuscript was received for review in January 2014. It was accepted for publication in October 2014.

Address correspondence to: Todd R. Fredricks, D.O., Department of Family Medicine, OUHCOM, 244 Grosvenor Hall, Ohio University Heritage College of Osteopathic Medicine, Ohio University, Athens, OH 45701; fredrick@ohio.edu.

DOI: 10.3357/AMHP.3954.2015

for more than a few hours in temperatures of just 31°C.[3] Complaints of headache and nausea during these periods were also reported anecdotally to the primary investigator by various crewmembers and such symptoms have been associated with formal studies of heat stress.[14] The primary investigator also witnessed aircrew members removing fire retardant clothing prior to departure in an effort to mitigate discomfort in high cabin temperatures. This is an obviously risky action that completely negates the fire protection afforded to aircrew by the garments and has implications for crew survivability in the event of an accident. The aircrew reports and direct operational observations led the principal investigator to arrange three flights during nominal operations to monitor Shorts Brothers 360 (Shorts 360) aircraft crew response to cabin temperatures and to document cabin temperature data.

METHODS

The aircrews reporting physical issues with aircraft temperatures operated the Beechcraft King Air 200 (BE-200) and the Shorts 360. The majority of dehydration and toileting complaints came from BE-200 crewmembers. Operational limitations in the theater allowed only static ground temperatures to be recorded for the BE-200 and no in-flight measurements were taken. These data were purposely omitted from this study to avoid confusion with the Shorts 360 data. Permission to fly three operational missions as a medical observer was obtained from the contractor operating the Shorts 360 platforms and observations were made during three operational missions over Iraq. No internal review board was available in Iraq to gain permission to measure pilot core body temperatures, so only dry bulb measurements were taken of the interior of the aircraft.

Apparatus

Three identical Acurite (Lake Geneva, WI) digital thermometers with temperature sensor probes and humidity detection capability (model number 00891A2) were used to take measurements. Equipment availability limitations in theater led to the use of these devices. Though humidity measured did correlate with reported conditions obtained from U.S. military weather services, the measured values were outside of the manufacturer's reported range of the thermometers. The thermometers were tested for accuracy against a Welch Allyn (Skaneateles Falls, NY) Sure Temp model 690 thermometer with the probe placed in water at a temp of 27°C and left exposed to ambient air at 27°C. All thermometers were within ± 2°C of one another. Once calibrated, the three Acurite remote sensors were secured together in a manner such that the individual sensors did not make contact with one another but were aligned in the same plane via the bundling of their respective attachment wires.

Procedure

Two locations were identified for measurements in the Shorts 360 platform (**Fig. 1**). All Shorts aircraft were painted a light gull gray color (Federal Standard 36440) and operated only from concrete or asphalt surfaces. The first location (PI) was just below the overhead center panel at the level of the pilots' heads. This location afforded the closest still air location to the pilots while avoiding any exposure of the sensor to direct sunlight. The second location (SEN) was at head level in the rear cargo compartment at the aft crewmember's station. This location is approximately 2 m aft of the forward cabin bulkhead separating the cockpit from the cargo hold. The entire Shorts airframe is open to air circulation during all phases of flight and is unpressurized. By opening a relatively large (~930 cm^2) left side cockpit window, the entire aircraft interior air volume can be rapidly exchanged via ram air effect with cabin flow exiting the open aft passenger door. This results in highly effective cabin cooling after takeoff. This is phenomenon is illustrated in the accompanying figures by the rapid decline in PI temperature during the initial climb to operational mission altitude.

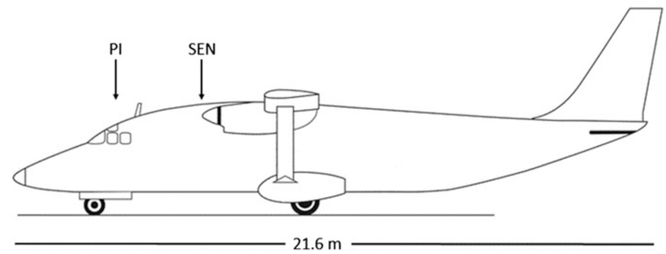

Fig. 1. Shorts 360 platform with approximate location of data collection points: Pilots (PI) and Sensor Operator (SEN).

The negative effects of hypoxia on complex task performance are compounded with increasing altitude and they persist after descent.[4] Nasal cannulas are suitable for oxygen support up to an altitude of 18,000 ft (5486 m) per the Federal Aviation Administration OK-09-439 Advisory Pamphlet. The principal investigator obtained a dedicated nasal cannula system to support oxygenation during the flights. All observed crewmembers used supplemental oxygen via nasal cannula for operations above 8202 ft (2500 m) mean sea level. The nasal cannulas were connected to the aircraft onboard oxygen system. Only two of nine crewmembers were observed using fingertip pulse oximetry to measure S_pO_2 during the missions. A lack of internal review board approval precluded recording this data. For purposes of observation at 14,107.6 ft (4300 m), the primary investigator noted a stable 97% S_pO_2 on his own pulse oximeter while on supplemental oxygen. He then purposely removed his nasal cannula, allowed 15 min for desaturation, and measured a stable S_pO_2 of 74%.

All three Shorts 360 flights were conducted during periods of daylight in cloudless skies. Recording of temperatures began with the aircraft prepped and crew positioned just prior to engine start. The aircraft were positioned on an unshaded ramp for at least 1 h prior to the initial measurement being taken. Recording ended with engine shutdown at the end of each flight. Measurements were taken at 30-min intervals at each station, respectively, and the sensors were allowed to equilibrate for a full 5 min prior to recording each data point. Outside air temperature (OAT) was recorded from the aircraft's OAT thermometer and this was measured against field weather reports. This data is included to show the difference between cabin temperatures and outside ambient air temperature. Humidity was measured and correlated against local field reported conditions. Humidity data is presented here for all flights, but the humidity data for flights 1 and 3 was inconsistent. Only flight 2 showed consistent readings at level operational altitude between measurement periods without display fluctuations. Constraints associated with safety and positioning of the probes during the taxi, takeoff, climb, descent, and landing phases of the flights resulted in data at the SEN station not being recorded.

RESULTS

The cockpit experienced elevated temperatures during periods of long taxi. This was compounded by the greenhouse effect created by the windshield and forward windows. This is illustrated in the figures by the constant initial altitude and rapid increase of temperatures at the PI station (**Fig. 2**, **Fig. 3**, and **Fig. 4**). Temperatures approaching 50°C were observed and the pilots endured these temperatures for periods of up to 1 h prior to departure. The cabin temperatures were consistently higher than measured OAT throughout most of each flight. The lower cabin temperature in relation to the OAT seen at the end of each flight is attributable to the rapid descent profiles used to return to base at the end of each mission. The data itself is explanatory in graphic form. Temperature and humidity data collected followed a steady trend line and the variance between individual sensors was within 1°C.

DISCUSSION

Queries of the Defense Technical Information Service and the U.S. Army Aeromedical Research Laboratory revealed no information or literature that document operational cabin temperatures for the Shorts. The principle investigator could find no scientific literature that quantified or discussed observations of crew performance and environmental temperatures in either the Shorts 360, C-23 (a dedicated military variant of the Shorts 360), BE-200, or the C-12 (a dedicated military variant of the BE-200). The advantage of using a COTS platform to support new aerial missions as opposed to the novel development and military procurement of mission specific aircraft has been to increase the speed of implementation of the supported system. The disadvantage of using COTS platforms is that they do not

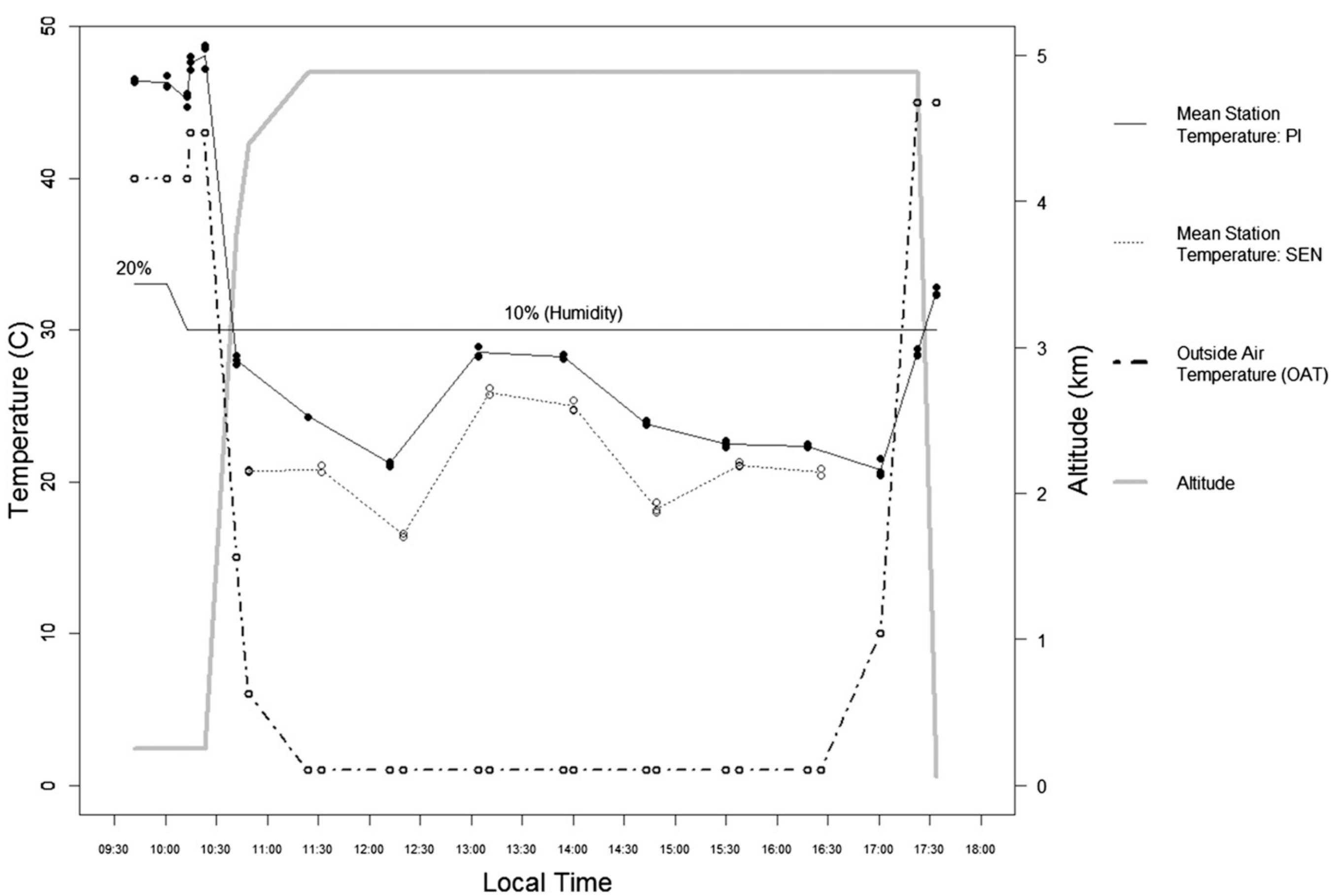

Fig. 2. Flight number 1, 21 August 2011, Central Iraq. Solid black line: mean station temperature PI; dotted grey line: mean station temperature SEN; black dashed line: outside air temperature; and light grey solid line: altitude.

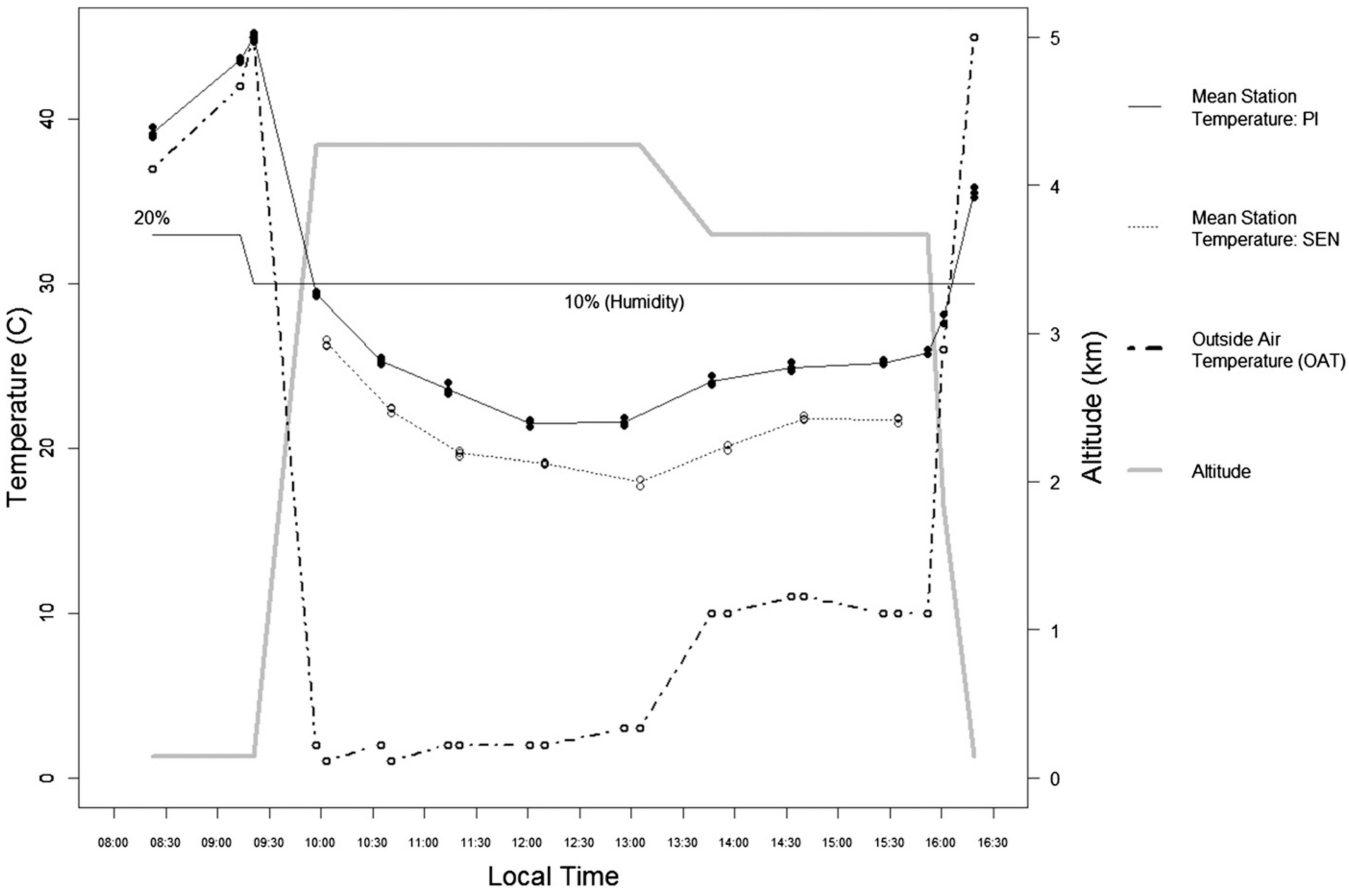

Fig. 3. Flight number 2, 22 August 2011, Central Iraq. Solid black line: mean station temperature PI; dotted grey line: mean station temperature SEN; black dashed line: outside air temperature; and light grey solid line: altitude.

easily allow military specific aircrew support needs to be identified and addressed.

An example of military aircrew specific thermal support is the Air Warrior Microclimate Cooling Garment widely used by U.S. Army helicopter crewmembers.[12] This system has been validated to improve crew performance and decrease physiological stress in HAT.[19] The primary investigator has flown multiple missions with Sikorsky Blackhawk (UH-60) crews using this system in Iraq and aside from anecdotal reports of occasional "clamminess," all soldiers using the system reported greatly improved functionality and comfort while flying in HAT. This system was not deployed on the COTS aerial platforms of concern in this paper. In addition it should be noted that in normal flight operations a UH-60 is highly ventilated, facilitating evaporative cooling effects in well-hydrated crews. Facilitated evaporative cooling in armor wearing combatants in HAT environments has been shown to reduce physiological stress.[5]

The high temperature data recorded during the Shorts 360 taxi poses concerns for the BE-200. The BE-200 is designed for pressurized climate-controlled flight. The air conditioning systems are not effective when pilots use taxi power settings. The BE-200 has only a very small opening window (~190 cm^2) in the cockpit that is entirely inadequate for ventilation while on the ground. Unlike the Shorts it is not designed to be opened during flight and the aft cabin door cannot be kept open during ground or flight operations. Several studies have documented thermal stress issues in dedicated military platforms with similar crew support systems.[2,7,15] The BE-200 frequently flies in instrument flight conditions and under instrument flight rules, necessitating a high mental workload on the aircrew. The effect of HAT on flight crew performance has been documented and there is an inverse relationship between desired performance and cabin temperatures.[9] This raises concerns for complex phases of flight such as approach and landing after long-duration mission HAT conditions.

Inoue et al. reported the relationship between core temperatures, perspiration, and linearly increasing ambient temperatures, but their study only measured these relationships up to 60 min of duration to a top ambient temperature of 40°C and in a population that was seated in an open room and clothed only in swimming trunks.[10] The negative effects of heat-induced physiological stress on flight performance have also been confirmed by Reardon et al.[18] While Reardon's study examined performance in full chemical protective gear (MOPP4), the end point of measurements was at 40°C, so at high temperatures without MOPP4 equipment it can be inferred that some degradation of performance could occur.

Some limitations of this study must be mentioned. Foremost was the use of on-hand measuring equipment. Due to the

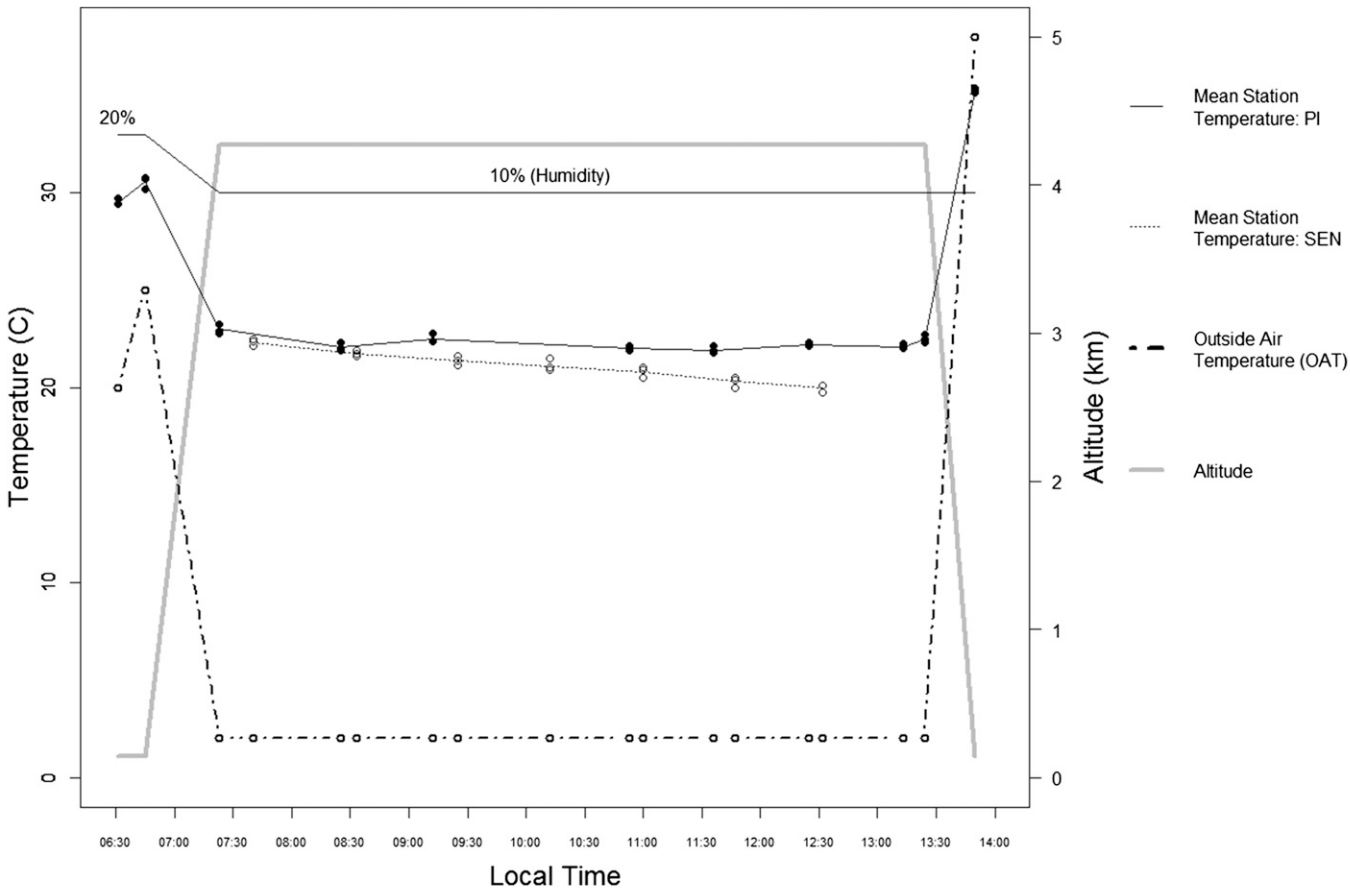

Fig. 4. Flight number 3, 26 August 2011, Northern Iraq. Solid black line: mean station temperature PI; dotted grey line: mean station temperature SEN; black dashed line: outside air temperature; and light grey solid line: altitude.

timing of data collection and the reduction of the theater assets, only dry bulb measurements were taken. While great care was taken to shield the thermistors from direct solar radiation, the study would have benefitted from more data point collection through both dry and wet bulb methods.[1,8] The data show a generally linear relationship between ambient OAT and cockpit temperatures,[8] so the data are compelling to illustrate the impressive variability of cockpit temperatures in the Shorts platform across its flight profile.

The single most desirable parameter for comparison in this study would have been core temperatures for each crewmember during flight, but lack of available equipment and inability to access timely internal review board approval precluded obtaining such a data set. Due to the deployment date of the primary investigator the data sets were gathered 1 mo after peak summer temperatures. While the data show extremes of temperature which the literature associates with reduced performance, it does not capture the highest duration of time and temperatures that the aircrews could be exposed to during operations.

The data have additional implications. Even with the rapid cooling effects seen in the Shorts platform from optimal ventilation after takeoff, the addition of increasing altitude to the effects of heat raise the question of how long performance is degraded. Flights 1 and 2 revealed cabin temperatures in excess of 48°C and both showed temperatures in excess of 39°C for over an hour. When these data are considered in light of aircrew self-reported, purposeful pre-mission dehydration efforts, the implications for crew endurance, physiological health, and mission effectiveness pose aeromedical and operational concerns. The Shorts 360 aircraft did have onboard toilet facilities and ample space available for ice chests to keep cool beverages cold during long-duration flight. The BE-200 platform is space-limited and does not allow for easy access to ice chests. The aircraft does have a built-in toilet, but the lack of servicing capability rendered them inoperative. Anecdotal reports from BE-200 crews suggest that attempts to use trash bags as toilet liners to hold human waste led to intolerable degradation of cabin air quality. BE-200 platform temperatures were not measured while the aircraft was at altitude with its full electronic systems suite powered up. The thermal implications on the aircrew of the mission aircraft with its electronics and communications systems powered up during extended taxi times in hot environments deserves further investigation.

The primary investigator also received comments from military personnel regarding the concerns that contractor-crewed platforms were not supported with aviation life support equipment (ALSE). The primary investigator never observed the use of dedicated ALSE by the ad hoc platform crews. Such equipment would include a flight helmet such as the HGU-56 with communication ear plugs, Air Warrior Microclimate Cooling Garment, survival vests, and portable urine collection devices. The author did observe U.S. Army C-23 aircrews using many of these devices.

The platform in this study utilized composite crews; at times having civilian and military personnel comprising parts of or total crews. The incorporation of ALSE systems for use by U.S. military personnel on COTS platforms used in an ad hoc fashion during military operations warrants further study. With respect to survivability a lack of standardization between purpose-built military and COTS platforms could pose implications for force protection and fighter management. The primary investigator would also point out that the nature of the Iraq theater in 2011 mandated that U.S. Army flight surgeons provided primary medical care services to nonmilitary U.S. civilian aviation contractors. This interaction provided significant insight into civilian contractor variances from U.S. Army standard ALSE practices and illuminated potential areas of increased risk and vulnerability of the civilian pilots during military-related aviation activities.

ACKNOWLEDGMENTS

Authors and affiliation: Todd R. Fredricks, B.S., D.O., and Masato Nakazawa, M.S., Ph.D., Ohio University Heritage College of Osteopathic Medicine, Ohio University, Athens, OH.

REFERENCES

1. Allan JR, Belyavin AJ, Higenbottam C, Nunneley SA, Stribley RF. Effect of cockpit temperature gradients on the validity of single-point measurements. Aviat Space Environ Med. 1979; 50(7):669–671.
2. Bollinger RR, Carwell GR. Biomedical cost of low-level flight in a hot environment. Aviat Space Environ Med. 1975; 46(10):1221–1226.
3. Breckenridge JR, Levell CA. Heat stress in the cockpit of the AH-1G hueycobra helicopter. Aerosp Med. 1970; 41(6):621–626.
4. Chiles WD, Iampietro PF, Higgins EA. Combined effects of altitude and high temperature on complex performance. Hum Factors. 1972; 14(2):161–172.
5. Chinevere TD, Cadarette BS, Goodman DA, Ely BR, Cheuvront SN, Sawka MN. Efficacy of body ventilation system for reducing strain in warm and hot climates. Eur J Appl Physiol. 2008; 103(3):307–314.
6. Froom P, Shochat I, Strichman L, Cohen A, Epstein Y. Heat stress on helicopter pilots during ground standby. Aviat Space Environ Med. 1991; 62(10):978–981.
7. Harrison MH, Higenbottam C. Heat stress in an aircraft cockpit during ground standby. Aviat Space Environ Med. 1977; 48(6):519–523.
8. Harrison MH, Higenbottam C, Rigby RA. Relationships between ambient, cockpit, and pilot temperatures during routine air operations. Aviat Space Environ Med. 1978; 49(1, Pt. 1):5–13.
9. Iampietro PF, Melton CE Jr, Higgins EA, Vaughan JA, Hoffman SM, et al. High temperature and performance in a flight task simulator. Aerosp Med. 1972; 43(11):1215–1218.
10. Inoue Y, Ichinose-Kuwahara T, Nakamura S, Ueda H, Yasumatsu H, et al. Cutaneous vasodilation response to a linear increase in air temperature from 28 degrees C to 40 degrees C in prepubertal boys and young men. J Physiol Anthropol. 2009; 28(3):137–144.
11. Joy RJ. Heat stress in Army pilots flying combat missions in the Mohawk aircraft in Vietnam. Aerosp Med. 1967; 38(9):895–900.
12. Kuwait City Monthly Climate Averages. World Weather Online. [Accessed 2014 Apr. 24]. Available from http://www.worldweatheronline.com/Kuwait-City-weather-averages/Al-Kuwayt/KW.aspx.
13. Microclimate Conditioning Systems. U.S. Army Natick Soldier RD&E Center website. [Accessed 2013 Nov. 12]. Available from http://nsrdec.natick.army.mil/media/print/MCC_Systems_Trifold.pdf.
14. Nunneley SA, Stibley RF. Heat and acute dehydration effects on acceleration response in man. J Appl Physiol Respir Environ Exerc Physiol. 1979; 47(1):197–200.
15. Nunneley SA, Stribley RF, Allan JR. Heat stress in front and rear cockpits of F-4 aircraft. Aviat Space Environ Med. 1981; 52(5):287–290.
16. Nunneley SA, Flick CF. Heat stress in the A-10 cockpit: flights over desert. Aviat Space Environ Med. 1981; 52(9):513–516.
17. Reardon M, Fraser B, Omer J. Physiological effects of thermal stress on aviators flying a UH-60 helicopter simulator. Mil Med. 1998; 163(5): 298–303.
18. Tikrit Iraq Monthly Climate Averages. World Weather Online. [Accessed 2014 Apr. 24]. Available from http://www.worldweatheronline.com/Tikrit-weather-averages/Salah-Ad-Din/IQ.aspx.
19. Reardon MJ, Fraser EB, Omer JM. Flight performance effects of thermal stress and two aviator uniforms in a UH-60 helicopter simulator. Aviat Space Environ Med. 1998; 69(6):569–576.