Evidence for $-G_z$ Adaptation Observed with Wearable Biosensors During High Performance Jet Flight

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INTRODUCTION: Few studies have evaluated physiological responses to high acceleration forces during actual flight and to our knowledge no normative data has been acquired by technologies such as wearable biosensors during high performance jet aircraft operations.

METHODS: In-flight physiological data from an FDA cleared portable triaxial accelerometer and bio-sensor were observed from five active duty F-18 pilots of the Naval Flight Demonstration Squadron (Blue Angels). Of the five pilots, three were formation pilots who flew lower G profiles and two were solo pilots who flew higher G profiles. Physiological parameters monitored were heart rate, respiratory rate, temperature, caloric expenditure, and duration of exposure to levels of acceleration.

RESULTS: Evaluated were 25 practice demonstration flights; 9 flights were excluded secondary to incomplete or inaccurate physiological data. We observed no significant bradycardia during a total of 189 maneuvers which met inclusion criteria for push-pull events (PPE) or isolated $-G_z$ exposures. Further analysis of 73 PPE revealed an overall significant rise in HR following the PPE, where mean heart rate was 106 (95% CI, 100:112) at the beginning of the push and 129 (95% CI, 123:135) following the pull.

DISCUSSION: A majority of the flights monitored provided reliable physiological data. Initial data suggests, contrary to currently held aeromedical doctrine, maneuvers such as the "push-pull" do not evoke vasovagal based bradycardic responses in aerobatic pilots. Possible explanations for these findings are sympathetic nervous system activation through adaptation and/or sustained isometric resistance from control inputs, both of which are areas of future research for our team.

KEYWORDS: in-flight biosensors, Batman syndrome, push-pull, acceleration tolerance.

Rice GM, Snider D, Moore JL, Lavan JT, Folga R, VanBrunt TB. *Evidence for $-G_z$ adaptation observed with wearable biosensors during high performance jet flight.* Aerosp Med Hum Perform. 2016; 87(12):996–1003.

We currently have systems to continuously monitor over a thousand mechanical components and systems in the aircraft, yet we currently do not continuously monitor the most important system: the pilot. The lack of in-flight physiological data on pilots has become an increasing concern in light of an upward trend in physiological hazard reports from several high performance aircraft platforms which use onboard oxygen generating systems. With regards to the U.S. Navy, fiscal year 2010 saw roughly 28 physiological hazard events reported in the F/A-18 and EA-18G, followed by a steady upward trend to the most recent year of data, 2015, with over 90 documented episodes.[19] These higher numbers can be attributed, to some extent, to an increase in aircrew awareness and reporting. The uncertainty around the nature and cause of these events points directly to the need for objective physiological data from the pilot to substantiate and more fully characterize these events.

Wearable biosensors and accelerometers have become ubiquitous in the field of exercise physiology and are fast becoming a tool to monitor workplace productivity.[25] They have been used in a number of scenarios, such as hypogravity,[7,18] dismounted soldier,[26] high-altitude sky-diving,[8] mountain climbing,[27] race car driving,[24] and centrifuge studies.[9] Despite these recent advanced technological applications of monitoring in extreme environments, current literature regarding the acquisition and monitoring of physiological information during high performance jet aircraft flight is lacking. In 2003, Kobayashi

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This manuscript was received for review in March 2016. It was accepted for publication in August 2016.

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DOI: 10.3357/AMHP.4609.2016

documented the efficacy of monitoring cerebral oxygenation during aircraft combat maneuvers using near infrared spectroscopy.[13] Unfortunately, no further studies acquiring normative data using this technology have been published. The closest attempt was by Di Rienzo et al., in 2010, who published a nonpeer reviewed technical report evaluating the effect of gravitational stress on heartrate variability using a cotton/elastin smart vest embedded with biosensors.[6] Although both Kobayashi and Di Rienzo's studies were performed on flight officers not at the controls, they demonstrated that current technology was capable of providing flight physiological data that could be obtained in a reliable, nonobtrusive manner during high performance jet aircraft maneuvers.

Of interest, Di Rienzo reported a reduction in both RR interval and standard deviation of normal intervals following a 5-s negative G_z and subsequent 15-s positive 5 G_z. This apparent increase in sympathetic tone was not consistent with several centrifuge,[1,11] tilt-table,[10,22] and small in-flight reports[2,3] which demonstrated a decrease in G tolerance secondary to an increase in vagal tone following "push-pull" maneuvers. Although the Di Rienzo paper was a technical report with several methodological constraints, it provided a critical takeaway. The physiological data acquired in this dynamic cockpit environment was not in agreement with prior aeromedical doctrine, which had grown primarily out of centrifuge and tilt table studies. The primary objective of the first phase of our study was to validate wearable accelerometers as a viable surrogate for the internal navigation systems (INS) of high performance aircraft.[21] Acknowledging the inherent differences that the actual flight environment imposes on pilots compared to simulated flight, a secondary objective of this study was to acquire normative physiological data during high accelerative maneuvers. What follows is a description of the physiological results obtained from a wearable commercial off the self (COTS) biosensor during high performance jet aircraft maneuvers.

METHODS

Subjects

Participants were five Naval active duty F-18 pilots from the Naval Flight Demonstration Squadron (NFDS, Blue Angels) who were aeromedically cleared and provided informed consent to participate in the evaluation of wearable biosensors during high performance aircraft operations. Three of the five pilots were formation pilots who primarily fly lower G profiles in tight configurations. Two of the pilots were solo pilots who typically fly opposing high performance jet aircraft maneuvers with higher G profiles. The study protocols and procedures were approved by the Navy Medicine Operational Training Center's Scientific Ethical Review Committee under protocol number NMOTC2014.0005, and subsequently approved by a higher level institutional review board at the Naval Medical Research Unit-Dayton, Wright Patterson Air Force Base, OH, on March 7, 2014.

Equipment

The device used for this study was a COTS, FDA cleared, portable triaxial accelerometer and biosensor called the Zephyr BioPatch™ (Zephyr Technology, Annapolis, MD). The biosensor consists of a BioModule and holder; the module is 2.8 cm in diameter by 0.7 cm and the holder is 8.8 cm × 4.8 cm × 0.8 cm. The biosensor had a combined weight of 33 gm, an acceleration sampling frequency of 100 Hz, and a maximum range of G detection of ±16 G in any axis. The ECG feature within the biosensor had a sampling frequency of 250 Hz with a range from 25 to 240 bpm. R-R interval range was reported to be 150 to 250 ms and ECG amplitude was 8 to 15 mV. The respiratory rate feature had a sampling rate of 25 Hz with a sensing range from 0 to 70 breaths per minute. Temperature sampling frequency was 1 Hz with a range of 10 to 60°C. Power supply was an internal lithium cell battery, rechargeable via USB prior to flight. Battery life while the unit is not transmitting is reported to be 35 h, with data storage of up to 20 d.[28] Although there is substantial evidence that wireless technology does not interrupt communication and navigations systems during commercial airline flights,[23] we did not use the wireless function in flight.

Procedure

The biosensor was initialized and time stamped to Greenwich Mean Time by a coinvestigator prior to each flight. The biosensor was adhered to the pilot's bare chest via transdermal patch electrodes under their flight suit and recovered postflight for data download and analysis. Data analysis for the biosensor was performed using Zephyr's proprietary data analysis software Omnisense™[29] and Microsoft Excel. Acceleration exposure was determined from the internal accelerometer of the biosensor, which was previously validated to be a viable surrogate to the INS of the F/A-18.[21] The four main physiological parameters observed by the biosensor were heart rate (HR), respiratory rate, temperature (Temp), and kilocalorie expenditure (Kcal). Energy expenditure was estimated from the average heart rate during a given flight using the equation developed by Keytel.[12,15] Only physiological data that was acquired between takeoff and landing was analyzed. Physiological data was excluded if the devices were inadvertently turned off, fell off, or if the recordings were incomplete, or not internally consistent with the ECG recordings of the biosensor. Data was specifically analyzed for significant $-G_z$ and $+G_z$ maneuvers using the following definitions.

A significant $-G_z$ exposure was defined as a change in the acceleration environment meeting these criteria:

- Decrease in G_z below +1 G_z (straight and level flight);
- Decrease in G_z must drop below +0.5 G_z and be sustained for $\geq$ 1 s;
- Duration of decrease in G_z must be $\geq$3 s; and
- Average G_z over the duration of the $-G_z$ episode must be $\leq$ +0.5 G_z.

A significant $+G_z$ exposure was defined as a change in the acceleration environment meeting these criteria:

- Increase in G_z above +1 G_z (straight and level flight);
- Increase in G_z must rise above +5 G_z and be sustained for ≥ 1 s;
- Duration of increase in G_z must be ≥3 s; and
- Average G_z over the duration of the $+G_z$ episode must be ≥ +5 G_z.

Data was specifically analyzed for aerobatic maneuvers such as isolated $-G_z$ exposures and push-pull exposures. Isolated $-G_z$ exposures were defined as any significant $-G_z$ exposure not proceeded by a significant $+G_z$ exposure for a minimum of 30 s. Push-pull exposures were defined as significant $-G_z$ exposure followed within 3 s by a significant $+G_z$ exposure. $-G_z$ exposures were further characterized by intensity, where $-G_z$ (push) peaks were stratified into levels such that:

- Level I: +0.5 to −0.99 G_z
- Level II: −1.0 to −1.99 G_z
- Level III: −2.0 to −2.99 G_z
- Level IV: ≥ to −3.0 G_z

Following each flight, a coinvestigator administered a post-flight questionnaire to assess the comfort level of these devices during flight. The favorable comfort results have been described previously.[21] Flight profiles flown were that of a typical air show and varied depending upon the cloud ceiling and weather conditions.

Statistical Analysis

Descriptive statistics were calculated for G_z exposure, HR, respiratory rate, temperature, and energy expenditure and compared between formation and solo pilots. Standard *t*-test and 95% confidence intervals were calculated to analyze statistical differences between mean HR during initial $-G_z$ exposure and following the completion of the exposure. Chi-squared analysis, Fisher's exact test, and risk ratios were used to compare the categorical event of heart rate decrease in formation and solo pilots to both push-pull events and isolated $-G_z$ exposures. Significance level was set at $P < 0.05$ and data was analyzed using SPSS® statistical software.

RESULTS

A total of five F/A-18 pilots from the NFDS participated in this study from August 2014 to October 2014. Demographic information is summarized in **Table I**, with an average age of 33.4 yr, height of 184.9 cm (72.8″), weight of 83.9 kg (185 lb), and total prior flight hours of 2070. Resting blood pressures and heart rates averaged 124/66 and 66 bpm. Of the five F/A-18 pilots, two pilots flew solo flight profiles and three flew in formation profiles.

Of the 25 flights monitored, 16 flights were deemed viable for inclusion in this study. Five flights from the same pilot were excluded secondary to the biosensor's internal algorithm miscounting peaked ECG t-waves, resulting in a doubling of the heart rate for this pilot throughout each flight. This pilot's data was excluded in its entirety. Four flights were excluded secondary to incomplete heart rate recordings ("drop offs"), including one flight where the transdermal patch came off in flight under the pilot's shirt. Of the 16 remaining flights, 8 flights were monitored from formation pilots ($N = 2$) and eight were monitored from solo pilots ($N = 2$). **Fig. 1** summarizes the average duration of G exposure during each flight. The average duration of flight for formation pilots was 2607 s (43. 5 min) ± 217.6 s and the average length of a solo pilot pilot flight was 2581.5 s (42.7 min) ± 154.9 s. During a typical 43-min show, solo pilots averaged 854.2 s (33.1%) of time greater than +2 G_z or less than −1 G_z, whereas formation pilots averaged 631 s (24.2%) ($P < 0.001$).

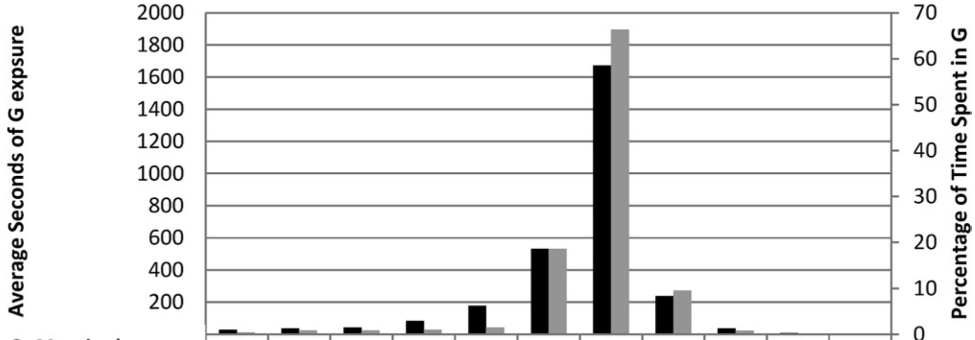
Table II summarizes the overall physiological data obtained from all flights which met criteria for inclusion in the study. Average heart rate for solo pilots was higher than for formation pilots at 104 ± 28 compared to 90 ± 15 ($P < 0.001$). Breathing rate was lower for solo pilots (14.3 ± 6.3 to 12.1 ± 6.7; $P < 0.001$). Temperature on average increased 0.3°C for formation pilots during a given flight and 0.7°C for a solo pilot ($P < 0.001$). Energy expenditure was measurably greater for one solo pilot compared to formation pilots and the other solo pilot, but due to the small sample size no statistical inference was made.

Mean HR responses to 73 push pull events (PPE) were examined as defined in the Methods section and illustrated in **Table III**. The average duration and magnitude of the push was 6.7 s and −0.5 G_z (−1.3:0.1). **Fig. 2** demonstrates a typical heart rate response to a level IV push-pull exposure. Upon analyzing the HR change overall, we found a statistically significant increase in HR from the beginning of pull to the end of the push [106 (95% CI, 100:112) to 129 (95% CI, 123:135)]. This statistically significant increase was found in all but one $-G_z$ severity stratification, Level II ($N = 17$), where despite a 7% rise in mean HR, the number of observations in this particular stratum was most likely too low. Moreover, as the severity of the $-G_z$ exposure increased, despite the low number of observations (Level III, $N = 15$, and Level IV, $N = 6$), the increase in HR following the pull remained significant. Of note, at the most severe $-G_z$ exposure, Level IV (< −3 G_z), there was a significant increase in mean HR following

Table I. Age, Anthropometric Variables, Resting HR, Blood Pressure, and Experience of NFDS Team.

PILOT	AGE	HEIGHT CM (INCHES)	WEIGHT KG (LB)	HR	SBP	DBP	YEARS ON TEAM	PRIOR FLIGHT HR
1	34	196 (77)	100 (220)	54	116	72	3	2300
2	34	183 (72)	82 (181)	64	118	64	2	1800
3	34	173 (68)	73 (161)	76	130	72	3	2000
4	33	183 (72)	75 (165)	80	134	62	4	2450
5	32	191 (75)	91 (201)	55	120	60	3	1800
AVG	33	185 (73)	84 (185)	66	124	66	3	2070

HR: heart rate; SBP: systolic blood pressure; DBP: diastolic blood pressure.



Gz Magnitude	>=7	>=6	>=5	>=4	>=3	>=2	>=1	>=0	>=-1	>=-2	>=-3
Solo Count	24	33.8	37.5	75.8	159	479.1	1510	213.1	34.5	6.9	3.6
Formation Count	10.9	24.4	22.3	26.4	39	483.9	1729.1	248.4	21.3	2.8	0
Solo %	1	1.3	1.5	2.9	6.2	18.6	58.5	8.3	1.3	0.3	0.1
Formation %	0.4	0.9	0.9	1	1.5	18.6	66.3	9.5	0.8	0.1	0

Fig. 1. Average G exposure time during eight practice shows for solo and formation pilots ($N = 16$ total).

the push as well [88 (95% CI, 84:92) compared to 140 (95% CI, 125:155)].

As illustrated in **Table IV**, 116 isolated $-G_z$ exposures were examined. The average magnitude and duration of these isolated $-G_z$ exposures were 0.2 G_z (−0.2:0.6) and 8.7 s. Although there were occasional decreases in HR observed during these isolated $-G_z$ exposures, there were no significant episodes of bradycardia. Furthermore, as severity of these isolated $-G_z$ exposures increased, we observed a mean increase in HR. This HR increase reached significance during Level II (<-1 G_z) exposures [94 (95% CI, 86:103) compared to 121 (95% CI, 107:137)]. Unfortunately, despite a 22% increase in mean HR in our Level III group, the number of observations were too low ($N = 2$) to make a meaningful statistical inference [86 (95% CI, 59:111) to 105 (95% CI, 64:146)]. **Fig. 3** depicts a typical HR response to a level II $-G_z$ exposure.

In lieu of no observable bradycardic events (heart rate less than 55 bpm) occurring during any $-G_z$ exposures, we analyzed if any decrease in heart rate occurred during these exposures for formation and solo pilots. A decrease in heart rate was defined as a categorical event that occurred within 3 s of initial exposure to any PPE or isolated $-G_z$ exposure. Of the 73 PPE, 24 were observed from formation pilots and 49 were from solo pilots (**Table V**). Out of 24 PPE exposures, 7 resulted in a decrease in heart rate within 3 s for formation pilots, whereas only 1 PPE exposure resulted in a decrease in rate for solo pilots [odds ratio (OR) of 14.3 (CI 1.9–110), $P < 0.001$], equivalent to a large effect size. With regards to the 116 isolated $-G_z$ exposures, 15 out 39 events for formation pilots had decreases in heart rate, while 20 of 77 events resulted in heart rate decreases for solo pilots [OR of 1.4, CI 0.83–2.5, $P = 0.19$].

DISCUSSION

The Blue Angels represent a unique population of aviators in which to examine physiological adaptation to extreme flight environments. Their flight profiles are similar from practice to practice and, therefore, acceleration exposures are predictable, making them a semi-controlled operational population to evaluate. On the other hand, their repeated exposures to accelerative forces in the absence of typical support equipment (G-suits) compared to the average naval aviator makes their physiological responses to extreme acceleration potentially less predictive of the responses of average pilots, even average tactical combat jet aviators. We say potentially here because there is no in-flight normative physiological data with which to compare these findings. The data that we present in this descriptive study represents a starting point from which aeromedical researchers may begin to explore with the advent of new wearable technological biosensors.

Of the many COTS biosensors that are available, we chose

Table II. Physiological Observations Between Formation and Solo Demonstration Flights.

FLIGHT	DURATION (s)	MEAN G_Z (MAX:MIN)	MEAN HR ± SD	MEAN TEMP	TEMP DELTA	MEAN RR ± SD	MEAN ENERGY EXP
Form 1	2516	1.5 (7.1:−0.7)	100 ± 24	37.4	0.7	18 ± 7	348
Form 2	2326	1.6 (6.8:−0.5)	82 ± 17	37.0	0.3	18 ± 7	217
Form 3	2765	1.6 (7.8:−0.7)	75 ± 14	36.7	0.4	14 ± 7	209
Form 4	2864	1.7 (8.1:−1.2)	86 ± 14	37.4	0.1	14 ± 7	297
Form 5	2761	1.7 (7.6:−2.4)	98 ± 22	37.6	0	14 ± 7	309
Form 6	2514	1.8 (7.3:−2.5)	99 ± 13	37.5	0.3	13 ± 7	287
Form 7	2317	1.7 (7.6:−1.2)	88 ± 7	37.5	0.1	13 ± 7	205
Form 8	2799	1.8 (8.0:−2.4)	88 ± 9	37.5	0.1	12 ± 6	242
AVG	2607.8	1.7 (7.5:−1.4)	90 ± 15	37.4	0.2	14 ± 7	264
Solo 1	2656	1.9 (8.2:−3.2)	122 ± 33	37.8	0.3	14 ± 8	458
Solo 2	2371	2.0 (7.8:−3.3)	115 ± 35	37.5	0.8	15 ± 9	368
Solo 3	2216	1.8 (7.5:−3.0)	113 ± 25	37.6	0.5	15 ± 9	335
Solo 4	2702	1.9 (8.0:−3.0)	107 ± 22	37.6	0.2	13 ± 7	364
Solo 5	2791	1.9 (8.3: −3.2)	112 ± 25	37.7	0.4	13 ± 8	414
Solo 6	2432	1.7 (7.7:−2.8)	95 ± 30	37.5	0.2	10 ± 5	292
Solo 7	2729	1.8 (7.9:−2.8)	85 ± 29	36.7	1.2	10 ± 4	250
Solo 8	2755	1.8 (8.0:−3.3)	80 ± 22	36.7	0.8	11 ± 5	218
AVG	2581.5	1.8 (7.9:−3.1)	104 ± 28	37.3	0.7	12 ± 7	337.4

HR: heart rate; RR: respiratory rate.

Table III. Heart Rate Response to 73 Recorded Push-Pull Exposures During Aerobatic Flight Maneuvers.

PEAK $-G_Z$ EXPOSURE	# EVENT	MEAN PUSH $-G_Z$ (MIN:MAX)	MEAN DURATION (s)	MEAN HR AT START OF PUSH (95% CI)	MEAN HR AT 3 s INTO PUSH (95% CI)	MEAN HR AT END OF PUSH (95%CI)	MEAN PULL $+G_Z$ (MIN:MAX)	MEAN DURATION (s)	MEAN HR AT END OF PULL
Total	73	−0.5 (−1.3:0.1)	6.7	106 (100:112)	110 (105:116)	118 (113:125)*	5.8 (4.5:6.6)	5.1	129 (123:135)*
Level I 0.5–(−1.0)	35	0.1 (−0.2:0.4)	4.0	115 (106:124)	120 (111:128)	123 (114:132)	5.8 (4.4:6.6)	5.4	135 (127:143)*
Level II <−1.0	17	−0.8 (−1.7:0.0)	6.7	115 (102:129)	119 (105:133)	123 (107:138)	5.9 (4.7:6.7)	5.1	133 (117:148)
Level III <−2.0	15	−1.4 (−2.4:−0.5)	8.8	96 (87:104)	100 (92:108)	112 (101:123)	6.0 (4.7:6.8)	4.7	123 (113:134)*
Level IV <−3.0	6	−1.1 (−3.2:−0.4)	17.3	88 (84:92)	94 (89:99)	140 (125:155)*	5.7 (4.8:6.2)	4.5	154 (139:169)*

* $P < 0.05$, HR difference statistically increased compared to HR upon initial $-G_z$ exposure.

this particular biosensor because it incurred a very small footprint on the pilot, was comfortable, nondistracting, and did not impair the anti-G straining maneuver (AGSM) of the pilot during extreme acceleration. As cited previously, it has an internal accelerometer that was validated to be a viable surrogate to the aircraft INS acceleration sensor.[21] Despite the reliable accelerometer features of this device, the heart rate monitor provided reliable physiological data on only 16 of 25 flights (64%). Five flights were lost due to the internal algorithm of the biosensor incorrectly identifying t-waves as R-waves. This was only discovered by using the raw two-lead electrical data of this biosensor and constructing our own ECG rhythm strip; this was not a standard capability of the biosensor's software program. Four other flights were discarded secondary to sustained drop offs where the heart rate data would disappear for up to several minutes. These drop offs occurred unpredictably and did not appear to be associated with high accelerations or heart rates. Moreover, one drop off occurred secondary to the transdermal patch connecting the biosensor to the chest coming loose during flight under the pilot's shirt. This was avoided in subsequent flights by shaving the chest of the pilot and applying isopropyl ethanol to the skin prior to applying the transdermal patches of the biosensor.

Although the biosensor we chose to evaluate provided reliable physiological data for a majority of the flights monitored, this study should not be interpreted as an endorsement for using these biosensors to identify and characterize physiological hazards. In truth, by analyzing data from these biosensors we would have been able to characterize only a fraction of the physiological hazard reports, discussed in our introduction, that have been associated with aviation platforms using onboard oxygen generating systems.[19] For example, in the absence of a tachycardic response monitored by the biosensor, a physiological hazard would have been unlikely to be due to hypoxia or G-induced loss of conciousness. Although one could argue that some data is better than no data, incomplete data could be interpreted incorrectly, especially by individuals without the ability to distinguish erroneous information. If the information has the potential to impact military operations, these erroneous interpretations could have significant adverse outcomes. So, if we are to employ biosensors routinely in these environments, we will need a more reliable biosensor with internal algorithms that are better able to discern noise and with a low drop off rate. Moreover, if we hope to better access the cognitive status of our pilots during flight, oxygen saturation, cerebral perfusion, and perhaps EEG data should be evaluated and considered for continuous monitoring.

With regards to $+G_z$ exposure, during an average 43-min practice show, solo pilots experienced accelerations higher than $+2\ G_z$ on average 32% of the time as compared to 23% of the time for formation pilots. One might suppose that the $+G_z$ exposure that the Blue Angels incur during their demonstration shows is quite different from that of typical operational aircraft combat maneuvers (ACM). However, the literature suggests that during typical ACM performed by F/A-18s, up to 20% of the duration of each sortie is spent above $+2\ G_z$.[20] Perhaps where the aerobatic flight profiles of the Blue Angels deviate most from operational sorties may be in the amount of $-G_z$ exposure which is incurred during a given flight. The closest comparative evaluation of operational push-pull exposure was performed by Michaud[16]

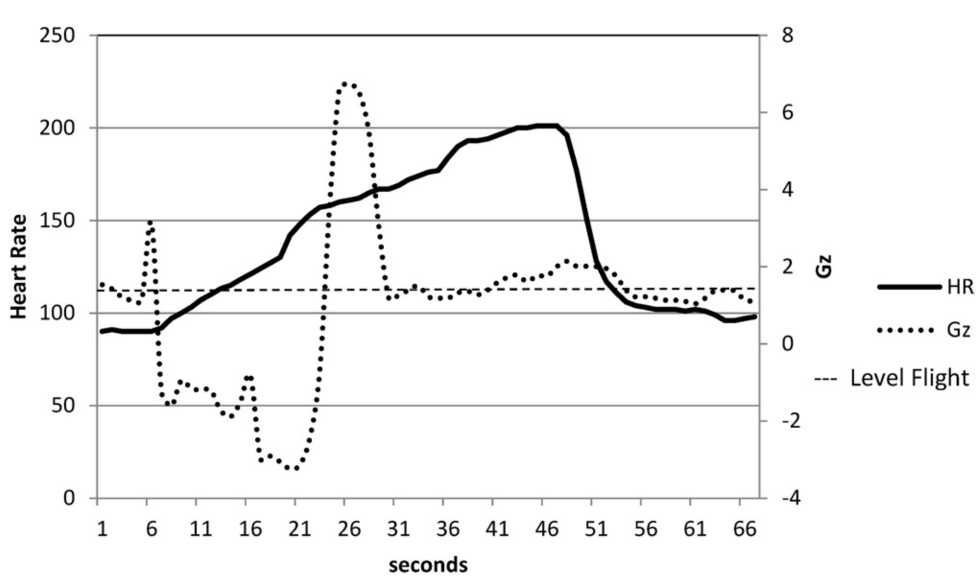


Fig. 2. Example of heart rate response to level IV push-pull exposure.

Table IV. Heart Rate Responses to 116 Isolated $-G_z$ (Push) Exposures During Aerobatic Flight.

PEAK $-G_Z$ EXPOSURE	EVENTS	AVG G_Z (MAX: MIN)	DURATION (s)	MEAN HR AT START OF PUSH (95% CI)	MEAN HR AT 3 s INTO PUSH (95% CI)	MEAN HR AT END OF PUSH (95%CI)
Overall	116	0.2 (-0.2:0.6)	8.7	103 (98:108)	103 (98:111)	106 (100:112)
Level I [0.5–(−1.0) G_z]	97	0.2 (-0.1:0.6)	6	105 (99:110)	104 (98:109)	103 (97:109)
Level II [< −1 G_z]	17	-0.3 (-1.4:0.5)	18	94 (86:103)	98 (90:107)	121 (107:137)*
Level III [< −2 G_z]	2	-0.8 (-2.1:0.5)	22.5	86 (59:111)	92 (67:130)	105 (64:146)

* $P < 0.05$, heart rate (HR) difference statistically different compared to HR upon initial exposure.

when he evaluated the HUD tapes from U.S. Air Force F-16 and F-15 combat training sorties, which entailed both basic aircraft maneuvers and ACM.[16] He defined PPE far more liberally than our study, declaring +0.8 G_z for 1 s to be a significant $-G_z$ exposure and +3 G_z for 4 s to be significant $+G_z$ exposure, with no minimum transition time specified. Our definition of a minimum average of +0.5 G_z exposure for 3 s, followed within 3 s by an minimum average of +5 G_z exposure was derived from the observations of Banks and Ryan that peak bradycardic events occurred, on average, 3 s after initial exposure.[1,22] Accepting 1-s exposures as significant $-G_z$ events, as Michaud's study defined, may result in counting events where the stimulation of the carotid baroreceptors was insufficient to trigger a vagal response, inducing bradycardia. Further, we observed occasional "blips" in the INS data from the F/A-18 and wearable accelerometers that reported $-G_z$ in the middle of a positive G_z exposure. Averaging G_z over a 3-s period ensured that these events were purely $-G_z$. Even with this liberal definition, Michaud found only 77 PPE during 242 engagements from 48 flights (1.6 events per flight). Whereas we found 73 events in 16 flights (4.6 events per flight) with a far stricter definition of significant $-G_z$ and $+G_z$ events. Additionally, the duration and magnitude of the pushes were also significantly higher in our study compared to Michaud's operational study, where the absolute minimum $-G_z$ observed was −0.7 G_z and maximum average duration was 5.2 s compared to our −3.2 G_z average peak magnitude and duration of 17.3 s.[16]

Predictably, we observed higher average heart rates for solo pilots compared to formation pilots who had less exposure to extreme G_z. The average temperature increase for solo pilots was higher, which is also consistent with their greater energy expenditure. Breathing rate was calculated by the biosensor as an average of the plesmograph recordings from the previous 30 s of flight. Correspondingly, we observed breathing rates below 5 for the pilots 20 to 30 s after each significant acceleration. Solo pilots who were exposed to more extreme acceleration during shows likely performed more AGSM and subsequently had more sustained periods of low breathing rates, resulting in solo pilots having a significantly lower breathing rate than formation pilots, 12 compared to 14. This delayed response from the biosensor respiratory rate is demonstrated in the online video segment (10.3357/AMHP.4609sd.2016) at the end of the online push-pull video incorporated as a supplement to this manuscript.

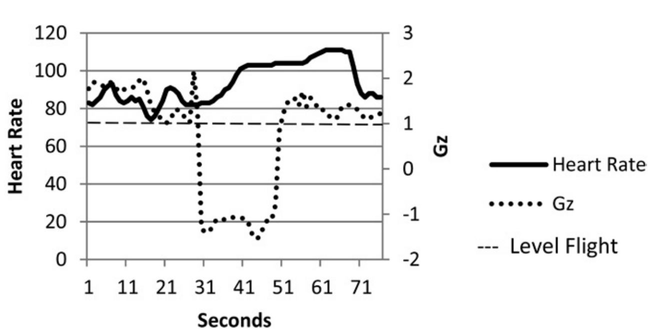


Fig. 3. Example of heart rate response to level II isolated $-G_z$ exposure.

Perhaps the most surprising observation during this study (and also illustrated in the video) is the heart rate response to the push component of push-pull exposures. During a combined 189 maneuvers which met our criteria for push-pull and isolated $-G_z$ exposures, we found no significant bradycardia. On the contrary, we observed an overall statistically significant increase in HR between the initial $-G_z$ exposure during the push and HR immediately after the pull. These HR increases were more pronounced with increasing severity of $-G_z$ exposure. These findings are consistent with Di Rienzo's 2010 technical report,[6] and contrary to currently held aeromedical doctrine born primarily from centrifuge and tilt table studies that have observed bradycardia during negative G_z exposures.[1,10,22] Potential reasons for the observed physiological differences between our in-flight studies and simulated studies range from increased work load during in-flight operations, accelerative adaptation, and currency of more experienced pilots.[4] For example, in 1972, Mohler wrote of the importance of "recency," what we often refer to now as "currency," with regards to G tolerance and stated that "a layoff of some days or weeks can result in lowered G-tolerance." He continues to describe a famous aerobatic pilot who routinely hung himself upside down in a harness to prepare himself for negative G_z for upcoming air shows.[17] Now, over 40 yr later, currency is considered a part of aeromedical doctrine and repeated $+G_z$ exposure has been demonstrated during simulated aircraft maneuvers to provide a compensatory response, primarily through a carry-over of vasoconstriction.[14] However, negative G_z adaptation, coined as "Batman Syndrome" by Mohler,[17] has not been previously verified physiologically to occur during simulated or in-flight operations and our results suggest that this phenomena may exist.

An alternate explanation for this observed $-G_z$ tolerance among the Blue Angels may lay in the isometric resistance their cockpit stick provides them throughout their flight. Beginning early on in their training season, their cockpit stick is gradually

Table V. Comparisons of Heart Decrease to Push-Pull Events and Isolated $-G_z$ Expsosures Between Formation Pilots and Solo Pilots.

	PUSH PULL EVENT			ISOLATED $-G_z$ EXPOSURE		
	HEART RATE DECREASE	NO HEART RATE DECREASE	TOTAL	HEART RATE DECREASE	NO HEART RATE DECREASE	TOTAL
Formation Pilot	7	17	24	15	24	39
Solo Pilot	1	48	49	20	57	77
Total	8	65	73	35	81	116
Odds Ratio (95% CI)	14.3 (1.9–110); $P < 0.005$			1.4 (0.83–2.5); $P = 0.19$		

spring loaded to a maximum weight of 40 lb resistance nose down to enhance their ability to perform precise stick control inputs. This requirement to provide a constant isometric force in their arm may be generating a baseline low level compression to the peripheral venous plexus of the upper extremities (similar to an AGSM). This isometric contraction may be sufficient to override the vagal response reportedly triggered by carotid baroreceptor stimulation induced by the $-G_z$ exposure. Future studies that expose naïve jet pilots to $-G_z$ exposure with and without this isometric resistance may provide new insights into potential mitigating strategies for $-G_z$ exposures, as the current recommendation from Davis et al. is to avoid the maneuvers altogether.[5]

It is possible that the physiological responses of formation pilots, who are exposed to less repetitive extreme G_z exposures, are indicative of an adaptation that lies somewhere between that of the solo pilot and a naïve jet pilot. Evidence for this was observed when analyzing any heart rate decrease to substantial $-G_z$ exposures, where formation pilots demonstrated a significantly higher rate of heart rate decrease to PPE [OR of 14.3 (95% CI, 1.9–110); $P < 0.005$]. This effect was less pronounced to isolated $-G_z$ exposures where their OR of having a decrease in heart rate was 1.4 (95% CI, 0.83–2.5; $P = 0.19$). Again, future studies evaluating naïve jet pilots to similar maneuvers are underway to confirm whether this is an adaptive phenomena we are observing.

In conclusion, the biosensor we evaluated was only reliable in obtaining viable physiological data during roughly two-thirds of observed flights. In contrast to previous simulated and in-flight studies, extreme $-G_z$ exposures during these aerobatic practice shows did not induce bradycardia in this population of highly experienced and seasoned jet pilots. Negative G_z adaptation and/or sustained isometric resistance are possible explanations for these findings. Future studies acquiring normative physiological data with wearable biosensors should be considered to elucidate a more comprehensive understanding of the human response to extreme accelerative environments.

ACKNOWLEDGMENTS

We would like to thank the Naval Flight Demonstration Team (The Blue Angels) for their unparalleled support of this study and dedication to aviation safety and flight innovation, and the Boeing Flight support personal, NAS Sherman Field, for their assistance in data acquisition from the Carrier Aircraft Navigation System (CAINS-2). Finally, appreciation goes toward to Valerie McCann, Navy Medicine Operational Training Center's librarian, for her tireless pursuit of relevant literature for this protocol.

The authors of this manuscript have no financial or other relationships that could be viewed as causing bias or conflict of interest.

The views expressed are those of the authors and do not necessarily represent the official position or policy of the U.S. Navy, the Department of Defense, the U.S. Government, or the University of West Florida.

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