Hemodynamic Responses and G Protection Afforded by Three Different Anti-G Systems

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BACKGROUND: UK Royal Air Force fast jet aircrew use three different anti-G systems, however, little objective comparison of the G protection they provide exists. The G-protection afforded by each system and associated hemodynamic responses were investigated.

METHODS: Ten subjects performed centrifuge acceleration exposures using Mk-10 (S1) and Mk-4 (S2) five-bladder anti-G trousers (AGT) and full coverage AGT plus pressure breathing for G-protection (PBG; S3). Measurements of relaxed G tolerance (RGT), eye-level blood pressure (BP_{eye}), lower body blood volume (LBV), stroke volume (SV) and total peripheral resistance (TPR) were made during gradual onset runs (GOR) and rapid onset runs (ROR). The subjective effort required to maintain clear vision at +7 and +8 G_z provided an indication of the protection provided by the system.

RESULTS: All systems moderated decreases in SV and BP_{eye} and increases in LBV under increased $+G_z$. S3 provided the greatest mean RGT during GOR (+6.2 G_z) and ROR (+6 G_z), reduced the effort required to maintain clear vision at up to +8 G_z, prevented venous pooling and afforded the greatest rise in TPR. The majority of indices revealed no difference between S1 and S2 although RGT during the ROR was greater with S2 (+0.25 G_z).

DISCUSSION: S3 effectively prevented pooling of blood in the lower limbs under $+G_z$, despite the use of PBG, and offers an advantage over five-bladder AGT. Given the similarities of S1 and S2, it was unsurprising that the majority of indices measured were similar. The objective measurement of hemodynamic parameters provides useful information for comparing the G-protection provided by anti-G systems.

KEYWORDS: Gz acceleration, blood volume, cardiovascular, blood pressure, anti-G trouser.

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Military fast jet aircrew may be exposed to sustained inertial forces up to nine times that of gravity acting in the craniocaudal direction ($+G_z$). $+G_z$ acceleration decreases cerebral perfusion pressure, and cerebral blood flow (CBF), resulting in peripheral light loss ("greyout"), central light loss ("blackout") and, ultimately, G-induced loss of consciousness (G-LOC).[10] The key physiological challenge during $+G_z$ exposure is the generation of a heart-level hypertension capable of overcoming the increased head-to-heart hydrostatic pressure gradient.[8] Cardiovascular reflexes assist in this, but with continually increasing G_z levels or sufficiently rapid onsets to high levels of acceleration even they cannot prevent G-LOC, and therefore additional methods are required to minimize the effects of $+G_z$. A number of solutions have been developed which primarily consist of utilizing a seat with a degree of backward tilt and anti-G trousers (AGT), inflatable garments that provide counter-pressure to the lower body in direct relation to the applied $+G_z$. The performance of anti-G straining maneuvers (AGSM) further supplements the support provided by engineering solutions.

The area compressed by the AGT, inflation pressure, and the rate and efficiency of pressure transmission to the body surface determine the support afforded to the arterial blood pressure.[4,15,30] Further protection, additive to that of the AGT,

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may be realized with positive pressure breathing for G protection (PBG).[8] The level of G-protection required and consequently, the anti-G system used depends on the aircraft flown. Highly agile aircraft are likely to demand greater protection than those less capable of sustaining higher levels of $+G_z$ acceleration. Within the UK Royal Air Force (RAF) two variants of partial-coverage AGT, the Mk-4 and Mk-10, are used. A full coverage AGT (FCAGT) with PBG is also employed.

All AGT elevate arterial blood pressure by increasing total peripheral resistance (TPR) and promoting venous return, which assists in the maintenance of stroke volume (SV) and thereby cardiac output (CO).[13] Despite these effects, the assessment of G protection effectiveness has largely been confined to subjective estimates of the G-level reached at predetermined visual end-points.[16,24,29] Notwithstanding its usefulness and parallel with aircrew visual symptoms, measurements are prone to significant day-to-day and between and within-subject variation.[17,20] Moreover, G-LOC can occur without preceding light loss at very rapid onset rates[10] while determinations of G-tolerance at moderate onset rates result in dynamic light loss symptoms, where initial loss of vision can be followed by recovery, complicating assessment.

Given the limitations of subjective measures of $+G_z$ tolerance, it is surprising that on reviewing the literature, only a single published study[16] can be identified in which G-protection afforded by different anti-G systems is compared using hemodynamic indices as objective physiological correlates. In this context, although it is widely accepted that FCAGT (with or without PBG) provide greater protection than partial coverage AGT,[10] the evidence for a difference in physiological response contributing to greater protection remains to be fully elucidated. The aim of the current study was to provide a direct within-subject comparison of the G-protection afforded by three different anti-G systems in use by the UK RAF and evaluate blood pressure, CO, SV, TPR, and lower limb blood distribution responses to $+G_z$ acceleration when using each system.

METHODS

Subjects

The study protocol complied with the principles of the Declaration of Helsinki and was reviewed and approved in advance by the RAF Experimental Medicine Scientific Advisory Committee and the UK Ministry of Defense Research Ethics Committee. Ten experienced centrifuge-trained participants (nonaircrew), whose characteristics are detailed in **Table I**, volunteered for the study. Prior medical screening comprised a comprehensive medical examination with emphasis on musculoskeletal (spinal) and cardiovascular health, including 12-lead electrocardiogram (ECG) and transthoracic echocardiography. Each subject provided written informed consent before participation. All had previously received extensive centrifuge training. In particular, they were all trained in the performance of the AGSM and could perform exposure to +9 G_z for 15 s. All were familiar with the assessment of relaxed G tolerance, and in the use of partial and full coverage AGT and PBG.

Table I. Subject Characteristics.

VARIABLE	MEAN	SD
Age (years)	28.8	6.3
Height (m)	1.81	0.08
Mass (kg)	82.1	9.2
SBP (mmHg)	126.2	11.3
DBP (mmHg)	66.7	6.0
MAP (mmHg)	88.7	11.0
HR (bpm)	74.8	15.1

With the exception of anthropometric data mean values were recorded over a 30 s period while the subject sat relaxed in the centrifuge prior to the first exposure. SD, standard deviation; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; HR, heart rate.

Equipment

Centrifuge. Acceleration exposures were conducted on a 9.14 m radius human centrifuge (Farnborough, UK). During centrifuge exposures subjects were seated and harnessed in an aircraft ejection seat reclined to 23° (Mk-16a, Martin Baker Aircraft Company Ltd., Higher Denham, Middlesex, UK).

Anti-G systems. Three anti-G systems were evaluated. System 1 (S1) and System 2 (S2) utilize Mk-10 and Mk-4 AGT, respectively, which are five-bladder partial coverage AGTs that apply counter-pressure to the anterior abdomen, both thighs and both calves through five interconnected bladders. While the S1 and S2 system appear similar, a better transfer of pressure to the abdomen has been noted with S2 due to slight differences in inflation characteristics of the AGT.[31] These systems were pressurized using an anti-G valve (**Table II**). System 3 (S3) utilized FCAGT plus PBG. FCAGT consist of a single inflatable bladder which covers the anterior abdomen and inguinal regions and provides fully circumferential coverage of each leg from a level just below the gluteal region to the lower calf. Inflatable sock bladders are also used. In addition, a chest counter-pressure garment, which inflated to the same pressure applied to the mask, was worn. A qualified survival equipment specialist fitted all equipment. Each anti-G system was evaluated on separate days. Further details of the three systems used are provided in Table II.

Physiological measurements. All data were recorded and stored on Chart software (LabChart v7, ADInstruments, Oxford, UK) after undergoing analog-to-digital conversion at a frequency of 200 Hz (Powerlab 16SP, ADInstruments, Oxford, UK). Heart rate (HR) was determined continuously from a three-lead ECG. Beat-to-beat blood pressure (Finapres 2300, Ohmeda, Louisville, CO, USA) was recorded using the volume-clamp method,[25] which is well-established for noninvasive trend monitoring in centrifuge studies[7,29] and has been shown to correlate well with intra-arterial line measurements.[21] From the recorded blood pressure waveform, using Modelflow analysis (BeatScope v1.1.0.6, FMS, Finapres Medical, Enschede, The

Table II. Description of Anti-G Systems Used.

	S1	S2	S3
AGT Designation	Mk-10	Mk-4	FCAGT
Coverage	Skeletal (~35%)	Skeletal (~35%)	Full-Coverage (~90%)
Material	Flame retardant Stable Aramid Fiber	Nylon	Flame retardant Stable Aramid Fiber
Anti-G Valve	VAG110-042A (Honeywell Aerospace, Yeovil, UK)	VAG110-042A (Honeywell Aerospace, Yeovil, UK)	Aircrew Systems Package (Honeywell Aerospace, Yeovil, UK)
Pressure Schedule for AGT	Step increase to 77 mmHg at +2 G_z increasing by 65 mmHg · G^{-1} thereafter	Step increase to 77 mmHg at +2 G_z increasing by 65 mmHg · G^{-1} thereafter	Increases by 75 mmHg · G^{-1} after +2 G_z
PBG	No	No	Yes (12 mmHg · G^{-1} increase beginning at +4 G_z)

Details of the anti-G systems used during the study. AGT, anti-G trouser; PBG, positive pressure for G protection.

Netherlands),[35] blood flow is modeled by simulating the behavior of the model under the applied arterial pressure pulsation. Stroke volume is then computed by integrating the model flow.[35] Subsequently CO and TPR can be computed. While changes in SV and CO measured by this method show close associations with invasive determinations made under orthostatic stress,[11] due to limitations with the technique, without invasive calibrations being performed, they are best used to describe trends in the data.[14,18] To correct for changes in the finger vascular state and account for potential drift the 'Physiocal' feature of the Finapres was enabled throughout testing.[36] The Finapres inflatable cuff was placed around the middle phalanx of the third digit of the left hand. Throughout testing subjects placed their arms on arm rests located either side of them which supported their arm at heart level throughout (the level of the aortic root was assumed to correspond with the manubrio-sternal junction).

Change in lower body impedance was measured by electrical impedance plethysmography using a Tetra-polar High Resolution Impedance Monitor (THRIM, UFI, Morro Bay, CA, USA).[22] This required attaching four electrodes to the surface of the skin. Prior to electrode placement the skin was abraded and cleaned with alcohol. Electrodes were secured using adhesive tape. Two current injecting electrodes, one placed on the dorsal surface of the left foot and left wrist, had a 1 mA, 50 kHz current passed between them. This current was detected by two sensing electrodes, one placed on the dorsal surface of the left foot (proximal to the current-injecting electrode) and one on the left anterior axillary line at the level of the sixth rib. The signals detected by the sensing electrodes were used to determine lower body impedance. Percentage changes in lower body impedance, from their respective pre-exposure baseline (recorded from 30 s immediately prior to centrifuge onset), were calculated from the recorded impedance. Previous studies have revealed that changes in impedance provide reliable estimates of blood volume changes[6] with the percentage change in impedance being inversely proportional to the change in blood volume.[26]

Experimental Protocol

Subjects began by performing two gradual onset rate (GOR; 0.1 G · s^{-1}) runs to allow determination of GOR relaxed G-tolerance (RGT_{GOR}). The anti-G system was disabled for the first GOR run to allow determination of RGT without anti-G system use (No-AGT) to give an indication of the subjects intrinsic physiological G-tolerance. The anti-G system was enabled for all remaining centrifuge exposures. A series of rapid onset rate (ROR; 1.0 G · s^{-1}) runs, plateauing at peak G_z for 10 s, were then performed to identify the subject's ROR relaxed G-tolerance (RGT_{ROR}). The subject was instructed to remain completely relaxed throughout all RGT exposures (i.e., no AGSM was performed). The final two runs of the session (ROR with AGSM) were rapid onset runs plateauing at 7 and 8 G_z for 15 s during which subjects performed the AGSM as required to maintain clear vision. A minimum of 2 min rest at +1 G_z separated all centrifuge exposures, if necessary, this was extended until the subject's heart rate returned to pre-exposure levels.

GOR runs for measurement of relaxed G-tolerance. Runs were terminated by the subject when 60° peripheral light loss occurred. This was determined using a horizontal bar 1.5 m in front of the subject, with red flashing lights at either end subtending a visual angle of 60°. Subjects looked directly ahead at a central white light throughout the run and pressed a button, which activated the centrifuge stopping mechanism, when the red lights were no longer visible. The GOR relaxed G-tolerance (RGT_{GOR}) of each subject was measured as the $+G_z$ level reached at the moment the subject pressed the stop button.

ROR runs for measurement of relaxed G-tolerance. The first of the ROR runs used to measure RGT was performed at a G_z level 1 G_z lower than the subject RGT_{GOR}. If mild or no visual loss was evident, the $+G_z$ level was increased by 0.2 or 0.4 G_z, respectively, for the next ROR. If more than 60° peripheral light loss occurred the acceleration level was decreased by 0.2 or 0.4 G_z, depending on the perceived rapidity of peripheral light loss, as reported by the subject after the run. This continued until the subject identified the exposure which most closely replicated the visual symptoms experienced during the GOR; this G level was taken as the RGT_{ROR} and only data from this run was used for analysis.

ROR with AGSM. These runs were included to allow evaluation of anti-G systems during conditions more representative of flight with the subject performing the AGSM. Following each run the effort required to prevent peripheral light loss was recorded (G_{effort}). Subjects were asked to rate G_{effort} on a scale of 1 to 10 where a score of 1 represents being completely relaxed and 10 indicates maximal AGSM effort.

Data Analysis

From the recorded blood pressure waveform systolic blood pressure was determined using a peak detection algorithm while mean arterial blood pressure was calculated as the integral of the waveform over each cardiac cycle divided by the cycle duration. Eye-level systolic blood pressure (SBP_{eye}) and mean arterial pressure (MAP_{eye}) were subsequently calculated by subtracting the hydrostatic equivalent blood pressure (height in centimeters × G level × 0.78),[1] where height represents the vertical distance from the blood pressure cuff (located at heart level) to the eye, from the values obtained.

GOR runs for measurement of relaxed G-tolerance. For each GOR the relationships between $+G_z$ and SBP_{eye}, MAP_{eye}, TPR, CO, SV, HR, and limb impedance were examined by calculating the slope of each variable (i.e., the change in each variable per G). The mean value determined from three consecutive heartbeats at seven discrete $+G_z$ levels, spaced equidistant between +1 G_z and RGT_{GOR}, was computed. Each of the values was plotted against the G_z level they were recorded at and the slope of the regression line between them determined. During the GORs performed without AGT inflation (No AGT), no statistically significant differences were identified between AGT conditions for any variable, so these data were pooled.

ROR for measurement of relaxed G-tolerance. During the RORs used to determine RGT_{ROR} the baseline values of all the variables of interest (HR, SBP, MAP, limb impedance, TPR, CO and SV) were calculated as the mean value over the 30 s immediately prior to the run. The mean SBP_{eye} and MAP_{eye}, maximum HR and limb impedance, recorded over the plateau period, were measured. In addition, TPR, CO and SV were determined from the final three heart beats recorded during the G_z plateau, allowing time for compensatory reflex responses to influence these variables. From these, the change in each variable was calculated as a function of $+G_z$.

ROR with AGSM. While the blood pressure waveform was recorded during the +7 and +8 G_z runs, measurement artifacts resulting from straining maneuvers[16] prevent reliable calculation of variables based on the blood pressure waveform. For these runs four different HR parameters were calculated: 1) baseline HR (HR_{bl}) – the mean HR recorded over 30 s immediately prior to the run; 2) mean HR (HR_{mean}) – the mean HR recorded during the plateau in G_z; 3) maximum HR (HR_{max}) – the maximum HR recorded during the G_z plateau; and 4) recovery HR ($HR_{recovery}$) – the mean HR recorded over a 30-s period immediately following G_z exposure.

Statistical Analysis

Normality of data distributions were assessed using the Kolmogorov-Smirnov test. Data found to be normally distributed were analyzed using repeated measures ANOVA while the Friedman Test was used for nonparametric data analysis. If ANOVA detected a significant main effect, post hoc analysis was performed using Fishers least significant difference test. Significance was determined at an alpha level of 0.05. For GOR, four conditions were compared (S1 vs. S2 vs. S3 vs. No AGT) while for all ROR runs three conditions were compared (S1 vs. S2 vs. S3). Unless otherwise stated, data are presented as mean ± SE. Statistical analysis was performed using IBM SPSS Statistics v22 (IBM Corp, Armonk, NY, USA).

RESULTS

Nine subjects completed all centrifuge exposures without incident. One subject experienced 'almost loss of consciousness' (A-LOC) during the +8 G_z exposure with S1 and did not attempt this exposure with S2. Therefore, the data reported for the +7 and 8 G_z exposures are for 9 subjects. An example of a blood pressure and heart rate recording during a ROR is shown in **Fig. 1**.

Group mean RGT data, for both GOR and ROR, are presented in **Fig. 2**. A significant effect of anti-G system was found on RGT_{GOR} [$F(3,27) = 17.017$; $P < 0.001$]. All AGTs increased RGT_{GOR} ($P < 0.001$) from the unprotected condition (i.e., No AGT; AGT worn but not pressurized). Mean RGT_{GOR} was significantly higher (+0.78 G_z) with S3 compared to S1 ($P = 0.017$) while no statistically significant benefit was found over the protection afforded with S2 (+0.51 G_z; $P = 0.123$). No differences in RGT_{GOR} were found between S1 and S2 ($P = 0.124$). A significant effect of anti-G system on RGT_{ROR} was found [$\chi^2(2) = 11.400$; $P = 0.003$]. During the rapid onset runs, RGT_{ROR} was significantly greater ($P < 0.05$) in S3 than both S1 (+1.37 G_z; $P = 0.005$) and S2 (+1.12 G_z; $P = 0.007$). RGT_{ROR} was also marginally greater with S2 compared to S1 (+0.25 G_z; $P = 0.044$).

The high $+G_z$ runs at +7 and +8 G_z required muscle tensing and, usually, a moderate or strong AGSM from most participants, particularly when wearing the partial coverage AGTs.

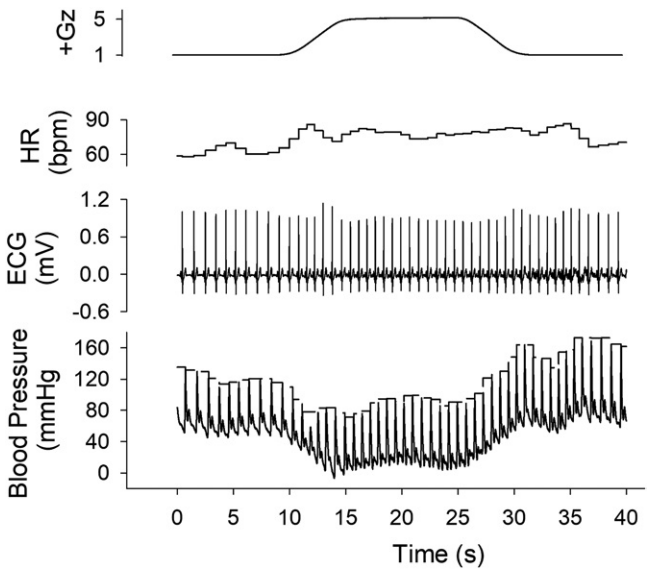

Fig. 1. Heart rate (HR), electrocardiography (ECG), eye level blood pressure waveform and systolic blood pressure at eye level (dashed line) recorded during a rapid onset rate exposure to 5.2 G_z in a subject wearing S3.

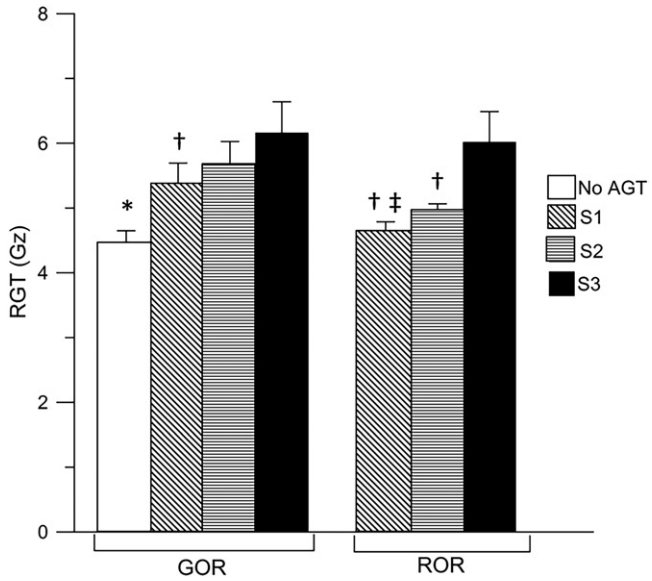

Fig. 2. RGT_{GOR} and RGT_{ROR} with S1, S2 and S3 (Mean ± SE). No AGT refers to a condition where AGT were worn but not pressurized. *Significantly different from S1, S2 and S3 ($P < 0.001$); †significantly different from S3 ($P < 0.05$); ‡significantly different from S2 ($P < 0.05$). RGT, relaxed G-tolerance; GOR, gradual onset run; ROR, rapid onset run.

G_{effort} was similar between S1 and S2 ($P = 0.773$ and 0.680 for +7 and +8 G_z runs, respectively) but was significantly lower with S3 at +7 ($P = 0.009$ and 0.01 for S1 vs. S3 and S2 vs. S3, respectively) and +8 G_z ($P = 0.005$ and 0.004 for S1 vs. S3 and S2 vs. S3, respectively). These subjective data were supported by measurements of HR; S3 attenuated the tachycardia seen under $+G_z$ [$F(2,18) = 27.594$; $P = 0.001$ and $F(2,18) = 13.377$; $P < 0.001$ for max and mean HR recorded during +7 G_z runs and $F(2,18)=10.390$; $P = 0.002$ and $F(2,18) = 11.754$; $P < 0.001$ for max and mean HR recorded during +8 G_z runs] and during recovery [$F(2, 18) = 8.571$; $P = 0.002$ and $F(2,18) = 8.932$; $P = 0.002$ for +7 and +8 G_z runs, respectively] compared to S1 and S2 (**Fig. 3**).

All anti-G systems reduced the decline in SBP_{eye} and MAP_{eye} and the rise in HR as a function of $+G_z$ during the GOR runs (**Table III**). Blood pressure responses were similar between S1 and S2. There was a tendency toward smaller decreases in SBP_{eye} and MAP_{eye} under $+G_z$ with S3 compared to S1 ($P = 0.062$ and 0.092, respectively) while no statistical difference between S2 and S3 was apparent ($P = 0.429$ and 0.351, respectively). The HR response under $+G_z$ with S1 and S2 was similar ($P = 0.809$) although the tachycardia recorded in both was greater (39%) than in S3 ($P < 0.001$ and $= 0.002$ for S1 and S2, respectively). A corresponding pattern of responses was found for the ROR runs, with smaller reductions in SBP_{eye} and MAP_{eye}, and increases in HR, in S3 compared with both S1 and S2 ($P < 0.05$). A smaller decrease in MAP_{eye} was also found in S2 compared to S1 ($P = 0.007$).

Compared to the unprotected exposure (i.e., No AGT), S1, S2, and S3 significantly increased impedance in the lower body during the GOR runs ($P = 0.049$, 0.022, and 0.005, respectively). Moreover, with S3, during both GOR and ROR exposures limb impedance increased under $+G_z$, indicating a prevention of blood pooling, whereas a footwards shift remained in S1 and S2 (i.e., limb impedance decreased; **Fig. 4**). The changes found with S3 were significantly different to S1 and S2 ($P = 0.005$ and 0.022, respectively).

During the GOR runs the anti-G systems reduced the fall in SV under $+G_z$ to a similar extent ($P = 0.001$, 0.018 and < 0.001, respectively for S1, S2, and S3 vs. No AGT). A contrasting response was observed for CO where greater decreases were apparent with S3 and No AGT ($P = 0.001$, $P = 0.032$, $P = 0.016$, and $P = 0.016$ for S3 vs. S2, S3 vs. S1, No AGT vs. S2, and No AGT vs. S1, respectively) compared to S1 or S2 (**Table IV**). TPR increased under $+G_z$ with more marked changes observed with S3 than S1, S2 and No AGT ($P = 0.007$, 0.013, and 0.009, respectively). S1 and S2 did not afford an increase in TPR above that found in the No AGT condition ($P = 0.575$ and 0.558, respectively). During ROR exposures there was no difference in the SV response under $+G_z$ between conditions ($P = 0.055$ in all cases), while decreases in CO were greater with S3 than S1 ($P = 0.001$). The rise in TPR under $+G_z$ acceleration was greatest in S3, with S1 producing the smallest effect ($P = 0.020$, < 0.001, and 0.020 for S1 vs. S2, S1 vs. S3, and S2 vs. S3, respectively).

DISCUSSION

This study evaluated the hemodynamic responses to the use of three different anti-G systems used by the RAF. Two were of essentially the same design (S1 and S2) while the third used full, rather than partial, coverage AGT and PBG (S3). As expected, the S3 anti-G system was superior, providing the greatest attenuation of the $+G_z$ induced decrease in head-level blood pressure while reducing the effort required to maintain clear vison under high $+G_z$. The majority of measures indicated that there was no difference between S1 and S2 although RGT_{ROR} was marginally greater with S2. Noninvasive estimates of SV and TPR, during GOR, revealed that although all the anti-G systems enhanced SV under $+G_z$, improved G protection was associated with an augmented response in TPR. A finding of particular interest was the contrasting response in lower body impedance, and consequently blood volume under $+G_z$ between the anti-G systems, with decreasing impedance (i.e., blood pooling) with the partial coverage anti-G trouser worn (S1 and S2) and increasing impedance with full coverage AGT.

Determination of G-tolerance is usually based on the $+G_z$ level reached at a predefined set of visual symptoms. However, subject motivation, experience, and understanding of the endpoint sought, can improve the reliability of the measurement.[5,17] These differences are minimized by using a within-subject approach which ensures the validity of comparisons drawn within a single study, although it remains difficult to compare these results against data acquired by other authors, particularly given the large number of influencing variables.[5] Objective measurements provide a potential solution, and in particular those metrics in which absolute values are readily comparable

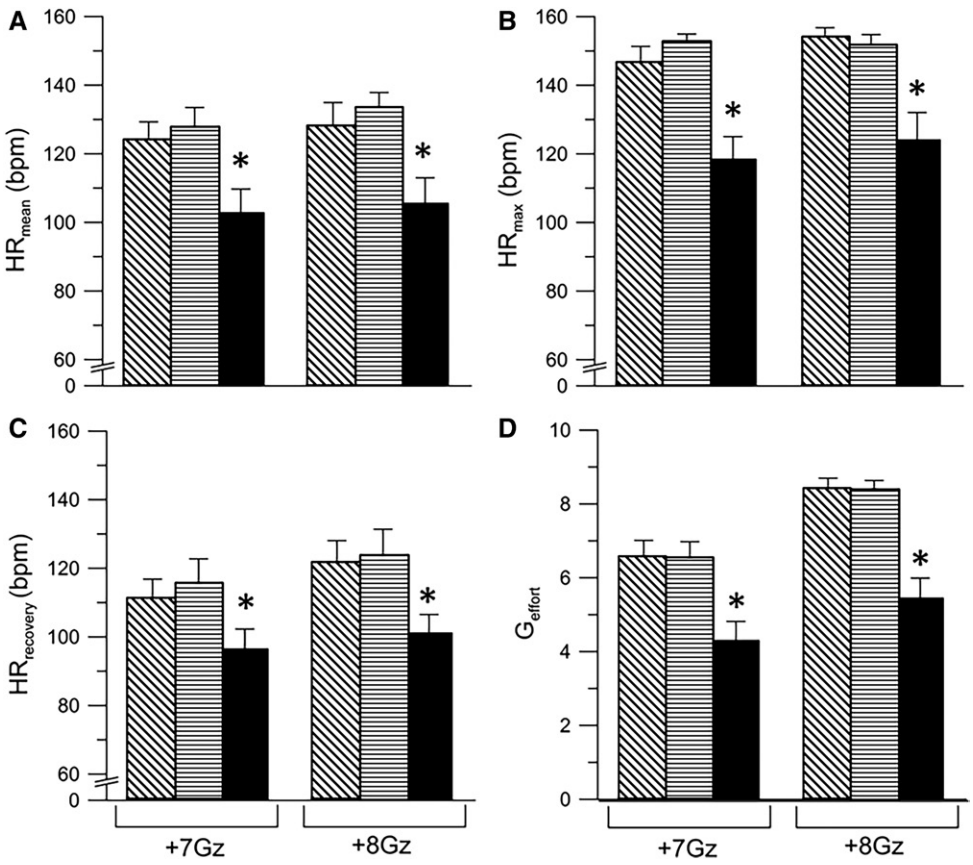

Fig. 3. Mean HR (A), maximum HR (B), HR recovery (C), and G_{effort} (D) recorded during +7 and 8 G_z exposures with S1 (white bars), S2 (stripped bars) and S3 (black bars) anti-G systems (Mean ± SE). Subjects were instructed to perform the AGSM as required to maintain clear vision. *Significantly different from S1 and S2 ($P < 0.05$).

between individuals (e.g., blood pressure). In this regard it is of note that the absolute values in G tolerance based on visual symptoms are somewhat lower than previous studies using similar (but not equivalent) anti-G systems,[3,32] whereas estimated +G_z level tolerances based on resting blood pressure and quantitative changes under +G_z would have suggested higher G tolerances may have occurred, particularly for S3. The difficulties in utilizing subjective measures of light loss to compare anti-G systems is further highlighted by the fact that SBP_{eye}, the best indicator of impending G-LOC, during ROR was the same with S1 and S2 whereas the subjectively determined RGT was lower with S1. As cerebral blood flow and consequently cerebral blood pressure will determine G tolerance objective measures of G protection (e.g., SBP_{eye}) should provide more reliable comparisons of anti-G systems than objective measures (e.g., RGT_{ROR}).

Theoretically, all else being equal, if heart-level BP remained constant as +G_z increased, the increasing hydrostatic pressure gradient would lower arterial pressure at eye-level by approximately 22 mmHg · G^{-1}. Estimation of SBP_{eye} allows us to calculate the effectiveness of different anti-G systems, under different conditions, relative to an 'unprotected baseline'. During GOR, SBP_{eye} fell by 18.3, 11.5, 10.1, and 7.9 mmHg · G^{-1} when using No AGT, S1, S2 and S3, respectively. Similar patterns emerged during ROR except that BP fell further, accounting for the lower G tolerance during ROR. The effectiveness of each anti-G system in mitigating the fall in eye-level BP during GOR and ROR, respectively, is; 64% and 59% for S3, 54% and 41% for S2, and 48% and 35% for S1. That the fall in the unprotected condition was less than that anticipated purely due to hydrostatic effects indicates that a level of 'protection' was provided in this condition. This reflects either the actions of an uninflated AGT, which has been estimated to increase in +G_z tolerance by 0.4 G,[24] an efficacious baroreflex response that not only maintained, but increased heart-level blood pressure, or a combination of both. Furthermore, it should be noted that the estimates for the effectiveness of each anti-G system during the ROR are likely to be conservative as heart-level blood pressure would be expected to fall without protection.[2]

Performance of the anti-G systems at higher G levels was assessed with subjects performing AGSM as vigorously as necessary to just maintain clear vision. Heart rates recorded during similar exposures have been used as surrogate measures of energy expenditure.[17] While determinants of +G_z "endurance" remain poorly understood and fatigue diminishes the ability to sustain repeated simulated air combat G profiles[9] identifying any factor that reduces energy expenditure during +G_z and facilitates postexposure recovery may be considered beneficial. Compared

Table III. Hemodynamic Responses to Gradual Onset Rate +G_z Acceleration.

VARIABLE	NO AGT	S1	S2	S3	STATISTICS
SBP_{eye} (mmHg · G^{-1})	-18.3 (1.7)*	-11.5 (1.4)	-10.2 (2.1)	-7.9 (1.4)	$F(3, 27) = 12.076$; $P < 0.001$
MAP_{eye} (mmHg · G^{-1})	-16.0 (1.0)*	-11.9 (1.0)	-10.8 (1.5)	-9.1 (1.1)	$F(3, 27) = 10.11$; $P < 0.001$
HR (bpm · G^{-1})	7.7 (0.5)*	5.8 (0.5)†	5.6 (0.7)†	3.5 (0.4)	$F(2, 27) = 11.674$; $P < 0.001$
SV (ml · G^{-1})	-9.5 (0.6)*	-5.4 (0.9)	-6.0 (1.3)	-5.8 (0.6)	$F(3, 27) = 8.610$; $P < 0.001$
CO (L · min^{-1} . G^{-1})	-0.28 (0.07)	-0.06 (0.09)†‡	-0.05 (0.07) †‡	-0.29 (0.05)	$F(3, 27) = 7.880$; $P < 0.001$
TPR (mmHg · min^{-1} · L^{-1} · G^{-1})	1.8 (0.3)†	1.7 (0.3)†	2.0 (0.6)†	3.9 (0.5)	χ^2 (3) = 10.320; $P = 0.016$

Mean (± SE) change in SBP_{eye}, MAP_{eye}, HR, TPR, SV and CO per G_z recorded during a gradual onset run (0.1 $G.s^{-1}$) to determine relaxed G-tolerance with the S1, S2 and S3 anti-G systems and AGT worn but not pressurized ("No AGT"). *Significantly different from S1, S2 and S3 ($P > 0.01$); †significantly different from S3 ($P < 0.05$); ‡significantly different from No AGT ($P < 0.05$). BP, blood pressure; HR, heart rate; TPR, total peripheral resistance; SV, stroke volume; CO, cardiac output.

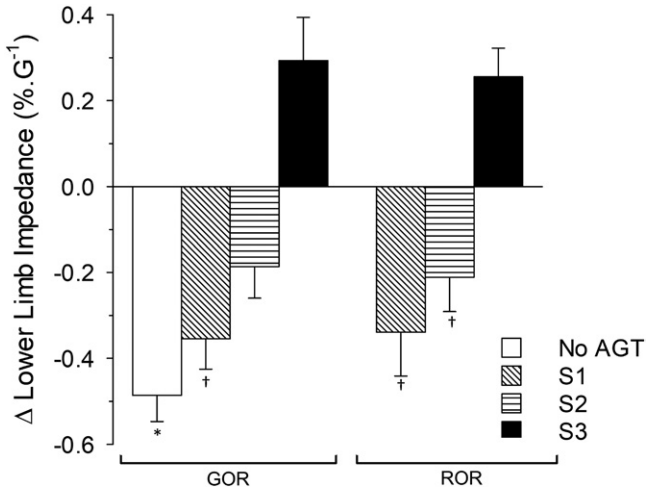

Fig. 4. LBV recorded during gradual and rapid onset acceleration exposures while using S1, S2 and S3 (Mean ± SE). No AGT refers to a condition where AGT were worn but not pressurized. *Significantly different from S1, S2 and S3 ($P < 0.001$); †significantly different from S3 ($P < 0.05$); ‡significantly different from S2 ($P < 0.05$). RGT, relaxed G-tolerance; GOR, gradual onset run; ROR, rapid onset run.

to S1 and S2, S3 substantially lowered the heart rate recorded during and following the centrifuge exposure (Fig. 2), indicating that the energy expenditure was lower which would aid in delaying fatigue onset. In addition the perceived effort during these runs was also lower with S3 further supporting the greater protection provided by S3. No meaningful differences in HR metrics or perceived effort were observed between S1 and S2 indicating that the energy expenditure and presumably the level of fatigue experienced using these systems was similar.

An important finding of the current study was the disparate response in lower limb impedance observed between anti-G systems. The impedance of the lower body decreased under $+G_z$ with the anti-G systems disabled indicating an increase in the fluid volume within this region in accordance with the expected pooling of blood within capacitance vessels below the heart.[13] Application of counter-pressure to the lower limbs and abdomen decreases venous compliance, hence, less pooling occurs under $+G_z$ with AGT inflation. This was observed in the current study through a smaller rise in limb blood volume (as assessed by measures of impedance) under $+G_z$ with S1 and S2 while S3 completely reversed the effects of $+G_z$ (i.e., blood was displaced headwards). This occurred despite the raised intrathoracic pressure accompanying PBG which would tend to cause blood to pool.[12] The prominent differences in the limb impedance response with S3 are likely due to the use of full rather than partial coverage AGT. Previous comparisons of lower limb impedance changes, used as a surrogate for blood volume redistribution, with partial and full coverage AGT also noted differences in blood volume distribution.[16] Extended coverage AGT prevented blood from pooling in the thigh and reduced it in the calf, whereas increases in blood volume in both regions were recorded with partial coverage AGT. Despite segmental volumes not being assessed, these findings are supported by the present study.

The cause of the exaggerated changes in LBV with full compared to partial coverage AGT cannot be discerned in the current study, although it is unlikely to be related to differences in pressurisation schedules as the two anti-G valves employed provide essentially identical intragarment pressures. Unlike other authors[3,16] we did not measure the segmental distribution of blood volume, instead choosing to record changes over the entire region of the body covered by the AGT. Measurements over specific areas may have allowed us to locate regional differences. For example, it is possible that blood pools in areas not covered by the partial coverage AGT (e.g., around the knee or feet) or that the counter pressure applied by tensioned fabric, rather than that directly applied by the air bladder itself, is not sufficient to prevent sequestration of blood within that region. In this context, the use of impedance plethysmography may prove to be a useful tool in the test and evaluation of anti-G trousers or G protection concepts. A further application may also be in the determination of an appropriate fitting tension for these garments.

To our knowledge this is the first study to compare estimated changes in SV and CO using the volume-clamp technique between different anti-G systems. Previous measurement using invasive methods (dye dilution) and those derived noninvasively by rebreathing techniques have recorded marked reduction in SV under $+G_z$ with a compensatory tachycardia ensuring smaller decreases for CO.[19,27,28] Only four studies have examined the effects of AGT inflation on SV and CO responses to $+G_z$ acceleration. Vettes et al. report that in one subject, AGT reduced the fall in CO from 24 and 36% at +4 and 5 G_z to 4 and 15%, respectively.[34] The tachycardia observed with $+G_z$ acceleration was also reduced. Using gradual onset rates and an echocardiographic technique, Tripp et al. determined that inflation of the AGT reduced the fall in SV under $+G_z$ though differences did not reach significance.[33] At +2 G_z, inflation of a FCAGT to 70 - 90 mmHg was sufficient to prevent any decrease in SV and CO, however, higher pressures, up to 215 mmHg, did not provide any additional benefit but did further raise mean head-level blood pressure.[23] Our results are in broad agreement; each of the three different anti-G systems attenuated the fall in SV under $+G_z$. It was, however, interesting to find that none were able to completely prevent its decline.

Table IV. Hemodynamic Responses to Rapid Onset Rate $+G_z$ Acceleration.

VARIABLE	S1	S2	S3	STATISTICS
SBP_{eye} (mmHg · G^{-1})	-14.3(1.50)	-12.9 (1.7)	-9.0 (1.1)*	F (1.30, 11.72) = 11.349; $P = 0.004$
MAP_{eye} (mmHg · G^{-1})	-14.2 (1.0)	-12.3 (1.2)†	-9.3 (0.9)*	F (2, 18) = 18.192; $P < 0.001$
HR (bpm · G^{-1})	6.5 (0.5)	7.1 (0.6)	5.1 (0.6)*	X^2 (2) = 5.600; $P = 0.041$
SV (ml · G^{-1})	-6.4 (0.7)	-8.6 (0.8)	-6.8 (1.0)	F (2,18) = 3.418; $P = 0.055$
CO (L · min^{-1} · G^{-1})	-0.11 (0.10)	-0.34 (0.10)	-0.42 (0.06)†	F (2, 18) = 4.287; $P = 0.03$
TPR (mmHg · min · L^{-1} · G^{-1})	1.3 (0.4)	3.1 (0.6)†	4.6 (0.5)*	F (2, 18) = 16.769; $P < 0.001$

Mean (± SE) change in SBP_{eye}, MAP_{eye}, HR, TPR, SV, and CO per G_z recorded during a rapid onset run (1.0 G · s^{-1}) to determine relaxed G-tolerance with the S1, S2, and S3 anti-G systems. *Significantly different from S1 and S2 ($P > 0.05$); †significantly different from S1 ($P < 0.05$). BP, blood pressure; HR, heart rate; TPR, total peripheral resistance; SV, stroke volume; CO, cardiac output.

The response in lower limb impedance and changes in SV and CO with S3 anti-G systems seem conflicting. Despite a reduced lower limb impedance recorded with S3 indicating that blood pooling was prevented under $+G_z$ and consequently venous return may be assumed to improve, SV was not enhanced compared to the other anti-G systems, while in the GOR exposures the reduction in CO under $+G_z$ was greater. The second of these is likely due to the reduced HR observed with S3, presumably due to smaller decreases in blood pressure under $+G_z$ and resultant moderation of the cardiac baroreflex. The first can be explained by the fact that although effective counter-pressure improves venous return (preload) the associated rise in aortic blood pressure will increase afterload. Thus, the increase in TPR with inflation of the AGT, and in particularly the pronounced increase with S3, offsets the beneficial effects of an augmented venous return on SV. That S3 afforded the greatest relaxed $+G_z$ protection of the configuration tested and smallest fall in head-level blood pressure suggests that increasing TPR under $+G_z$ is more important for $+G_z$ tolerance than the maintenance of SV, in agreement with previous research.[19]

Interestingly, despite the similarities in S1 and S2, while not always significant, there were differences in the hemodynamic responses and RGT recorded between them with a greater effectiveness noted in S2. Although not measured as part of the present study we have previously found that pressure transmission associated with the abdominal bladder of these AGT is less efficient with S1.[31] The importance of the abdominal bladder component of anti-G trousers have been highlighted in previous research indicating that it contributes not only to counteracting dislocation of blood to the abdomen and caudal displacement of the heart but also facilitating pressure transmission from the airway to the thorax.[7] Given the importance of the abdominal bladder to G-protection this should be considered as a potential area for modification to improve the G-protection associated with anti-G trousers.

There are several limitations to this study. Without calibration of the blood pressure waveform using, for example, hemodilution the absolute values estimated for CO, SV, and TPR using Modelflow procedures may be inaccurate and at best can only be used for trend analysis,[14,18] therefore only trends were reported. Due to constraints and technical limitations of working on the Farnborough centrifuge, invasive measurements of blood pressure could not be made. While a range of hemodynamics variables have been assessed along with G-tolerance the causality between variables has not been assessed – only comparison between anti-G systems. These measurements were selected as they have been suggested to contribute to the protection provided by anti-G systems. The centrifuge is limited to a maximum G onset rate of $1.0\ G \cdot s^{-1}$, somewhat lower than the capability of the aircraft in which these anti-G systems are deployed. The extent to which these findings can be translated to their use at higher onset rates, therefore, remains unclear. The requirement to assess the S3 anti-G system as a whole, including PBG, precluded direct garment comparison of the effectiveness of FCAGT with partial-coverage AGT and discrimination of the added benefit of PBG, particularly in the context of variable underlying subject G tolerance. The $+G_z$ exposures, for ethical and safety reasons, were performed in a prescribed order and though exposures were separated by a period of rest to ensure recovery, we cannot discount some carry over effect from the initial to final exposures. Importantly for this study these considerations apply to all three of the anti-G systems tested equally. Finally, limitations in using visual endpoints to determine RGT are well known.[17,20] As alluded to earlier, it is possible that lower RGT values reported may reflect additional variability of subjects in anticipating the intended endpoint.

S3 provides the greatest G-protection, enhances TPR, limits venous compliance and reduces the energy expenditure and perceived effort required to perform the AGSM more effectively than the other anti-G systems tested. Despite the similar designs of S1 and S2, S2 provides marginally greater relaxed G-tolerance due to enhanced TPR, although these slight differences do not translate to the energy expenditure or perceived effort required to perform the AGSM. Consideration of detailed hemodynamic responses provides direct evidence of the efficacy of different anti-G systems and enhances our understanding of the physiological responses to their use, complemented by measurement of lower body blood volume changes using impedance plethysmography.

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