Prevention of G-Induced Effects on Vision and Consciousness During Simulated Suborbital Spaceflight

Ross D. Pollock; Joseph K. Britton; Nicholas D. C. Green; Daniel Hendriksen; Peter D. Hodkinson; Ryan A. Anderton; Thomas G. Smith

INTRODUCTION: During centrifuge-simulated suborbital spaceplane flights, launch and re-entry frequently cause visual symptoms, and G-induced loss of consciousness can occur. G-related effects may be more prominent during re-entry from microgravity on actual flights. A modified anti-G maneuver that does not involve a breath strain and is suitable for members of the public may be effective against these effects.

METHODS: Recruited were 13 healthy subjects (age range 34–82 yr) who had experienced visual symptoms during centrifuge-simulated suborbital centrifuge profiles as part of a previous study. Onset and duration of greyout were recorded during an acceleration profile simulating spaceplane launch and re-entry in an upright seated position. The profile was undertaken twice: once in a relaxed state and once while undertaking anticipatory muscle tensing consisting of pre-tensing the leg and abdominal muscles (i.e., the muscle tensing component of a standard aircrew anti-G straining maneuver).

RESULTS: Muscle tensing was well tolerated and prevented 100% of greyout on launch and 54% of greyout on re-entry, as well as delaying the onset of greyout when it did occur on re-entry. Combined with the previous study's data, this indicates an overall population incidence of greyout of ∼70% on launch, falling to zero with muscle tensing, and ∼80% on re-entry, falling to ∼37% with muscle tensing.

DISCUSSION: Anticipatory pre-tensing of leg and abdominal muscles prevented greyout completely during the launch phase and partially during re-entry, and should be considered as part of routine suborbital spaceplane operations. Studies providing relevant data from actual flights are required.

KEYWORDS: spaceflight participant, high-G acceleration, $+G_x$, $+G_z$, AGSM, G-LOC.

Pollock RD, Britton JK, Green NDC, Hendriksen D, Hodkinson PD, Anderton RA, Smith TG. *Prevention of G-induced effects on vision and consciousness during simulated suborbital spaceflight*. Aerosp Med Hum Perform. 2024; 95(12):897–901.

Suborbital flights allow members of the public to travel to space commercially. The industry's development shares many parallels with the early history of air travel last century and, should this continue, suborbital flight is eventually expected to mature into a means of very high-speed global transportation.[1]

The $+G_x$ and $+G_z$ experienced during suborbital launch and re-entry stimulate physiological responses that can be significant.[2–4] While data from actual flights are not yet available, we recently used a centrifuge to simulate these hypergravity phases and characterize the resulting physiological responses in detail through continuous cardiovascular and respiratory measurements.[2] The study simulated various suborbital platforms and seating orientations relevant to current and potential future operations, including both spaceplane and vertical rocket-launched capsule flights.[1] We found that spaceplane acceleration

From King's College London, London, United Kingdom; the Royal Air Force Centre of Aviation Medicine, RAF Henlow, United Kingdom; and the UK Civil Aviation Authority, Gatwick, United Kingdom.

This manuscript was received for review in May 2024. It was accepted for publication in July 2024.

Address correspondence to: Prof. Thomas G. Smith, D.Phil., FRCA, Visiting Professor of Aerospace Medicine, King's College London, Centre for Human and Applied Physiological Sciences, Shepherd's House, Guy's Campus, London SE1 1UL, United Kingdom; thomas.g.smith@kcl.ac.uk.

DOI: https://doi.org/10.3357/AMHP.6511.2024

profiles, which involve greater magnitudes of $+G_z$, were generally well tolerated but generated highly dynamic changes in heart rate, blood pressure, and cardiac output, as well as frequent respiratory symptoms and hypoxemia associated with transient impairment of gas exchange.[2] During simulated spaceplane profiles, the incidence of G-induced visual symptoms was high, with most subjects reporting partial visual loss (greyout) and more than a quarter reporting complete visual loss (blackout). There was one episode of G-induced loss of consciousness (G-LOC), establishing that G-LOC can occur during simulated suborbital spaceplane flights.[2]

These effects were greater with spaceplane profiles in which occupants were oriented in an upright seated position throughout the flight, during which the incidence of visual symptoms was 71% for launch and 79% for re-entry. This compares with an incidence of 69% during a similar spaceplane profile in an earlier centrifuge study, in which greyout persisted in 15% of layperson subjects despite the use of a basic anti-G straining maneuver (AGSM) with a 'hook' (closed-glottis) breath strain.[5] The occurrence of lumbar strain injuries in a small number of subjects[5] highlight that extensive training is required to achieve an efficacious AGSM and to avoid injury. Furthermore, incorrect timing of the breath strain can reduce G tolerance due to either hyperventilation (too rapid) or impaired venous return (too slow).

Visual symptoms during suborbital spaceflights impact the subjective experience and may cause distraction for passengers and crew. In addition, such symptoms occur due to a fall in head-level blood pressure and are a sign that cerebral perfusion is reduced to a point where further impairment may lead to G-LOC and thus in-flight incapacitation.[6] Such a scenario is highly undesirable for passengers, while for controlling crew it presents a flight safety risk. Though a formal AGSM may be beyond the scope of private citizens undertaking commercial suborbital spaceflights, anticipatory muscle tensing limited to pre-tensing of leg and abdominal muscles without a breath strain component may be beneficial in reducing the risk of visual impairment and loss of consciousness. The current study aimed to determine whether anticipatory pre-tensing of leg and abdominal muscles can prevent visual symptoms during relevant suborbital spaceplane G profiles, with the overall goal of maximizing safe access to suborbital spaceflight.

METHODS

Subjects

The 21 subjects who had experienced G-induced visual symptoms at any point during our previous study[2] were invited to take part in these additional experiments. Some were unable to participate due to logistical or health reasons, and thus 13 were recruited. As in the preceding study, subjects were required to be in good health, as evidenced by holding a UK Civil Aviation Authority (CAA) Class 2 Medical Certificate (or higher), which is the UK standard required for private pilots. Other exclusion criteria, including pregnancy and BMI > $35\,kg \cdot m^{-2}$, were unchanged from the previous study.[2] The study was approved by the Ministry of Defense and King's College London Research Ethics Committees (2039/MODREC/21) and was conducted in accordance with the Declaration of Helsinki. All subjects provided written informed consent.

Equipment

The study was undertaken at the Royal Air Force High G Training and Test Facility (RAF Cranwell, United Kingdom) using a 7.5-m radius centrifuge with a representative F-35 Lightning cockpit installed in the gondola (seatback angle 22°). Acceleration was measured at head level in all axes. Subjects held a marker button in the left hand and pressed and held this to indicate the onset and duration of any visual symptoms (recorded via PowerLab and LabChart 8; AD Instruments, Oxford, United Kingdom). Subjects were video-monitored continuously and maintained two-way voice communication with the medical officer in charge.

Procedure

By design, all subjects had experienced greyout in the previous experiments. The G profile simulated suborbital spaceplane launch and re-entry in an upright seated position and was identical to the equivalent profile in the previous study.[2] The peak applied acceleration during the launch phase was +3.7 G_z and +3.6 G_x, and during re-entry was +4.0 G_z and +4.5 G_x (acceleration profiles shown in **Fig. 1**). Between the high-G launch and re-entry phases, $+G_x$ was off-loaded for approximately 30 s with a residual +1.2 G_z. Subjects undertook the G profile twice, once in a relaxed state and once while performing pre-tensing, consisting of pushing down on the rudder pedals while contracting the leg and abdominal muscles. The order (relaxed/pre-tensing) was counterbalanced, and the onset and duration of any visual symptoms were recorded.

Muscle pre-tensing was standardized as follows: participants received a standard briefing for the lower limb component of the standard AGSM that is routinely taught to fast jet aircrew (i.e., an AGSM without any breath strain component).[6] Specifically, this consisted of instructions to contract their calves, quadriceps, gluteal, and abdominal muscles. They were instructed to commence muscle tensing at the onset of high G, and to stop tensing when G_z had fallen back to +2 G_z following peak G (identified by an audio cue from the medical officer in charge). This provided a duration of muscle tensing of ~20 s for the launch phase and ~30 s for the re-entry phase. For relaxed runs subjects were instructed to remain relaxed in the absence of visual symptoms, and to perform leg muscle tensing only if greyout developed, consisting of simply pushing down on the rudder pedals while tensing the leg muscles to clear vision. Subjects did not wear G protection and did not perform the breath strain component of the AGSM. Exposures were separated by a minimum of 2 min idling at centrifuge baseline G level (+1.2 G_z). Recovery from any symptoms was confirmed before proceeding with each profile.

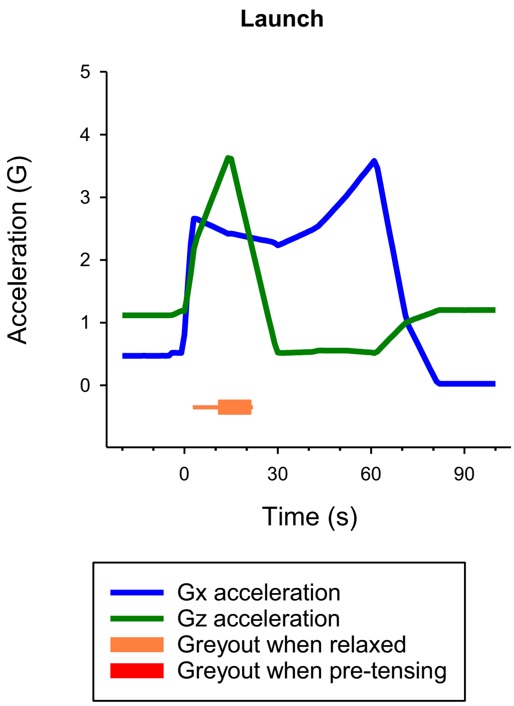

Fig. 1. Acceleration profiles and timing of greyout. Applied acceleration (+G_x and +G_z) is shown. The mean period over which greyout occurred is indicated by a thick horizontal box. The full range over which greyout was observed is indicated by a thin horizontal line. Blue lines: +G_x; green lines: +G_z; orange bar: greyout when relaxed; red bar: greyout when pre-tensing.

Statistical Analysis

Differences were assessed statistically using Student's two-tailed *t*-test for paired samples and were considered significant at the $P < 0.05$ level. Data are reported as mean ± SD unless otherwise stated.

RESULTS

There were 13 subjects (10 men and 3 women) with mean (± SD) age 53 ± 15 yr (range 34–82 yr), weight 82 ± 16 kg, height 1.76 ± 0.09 m, and body mass index 26 ± 4 (kg · m^{-2}). All subjects were in good health in accordance with the CAA Class 2 Medical Certificate standard. Acceleration profiles were well tolerated, and all subjects completed all G exposures. There were no reports of blackout and no episodes of G-LOC. Pre-tensing was well tolerated, with all subjects reporting no related muscle fatigue or other concerns related to its performance.

Visual symptoms occurred within a tight range of +G_z and +G_x, which is indicated on Fig. 1. Pre-tensing completely prevented visual symptoms during the launch phase and reduced the incidence of greyout during re-entry by 54% (from 13/13 subjects to 6/13 subjects). However, the subjects in this study were drawn from among only those individuals who experienced visual symptoms in the preceding study. In order to take this into account when considering the greyout rate in the current data, an overall (population) estimate for greyout incidence was calculated by applying the preventative effect of pre-tensing observed in the current study to the original incidence data published in the preceding study,[2] in which the incidence of visual symptoms during the corresponding G profile was 71% during launch and 79% during re-entry. Applying the preventative effect observed in the current study indicates that ~37% of the population would be expected to experience persisting greyout on re-entry despite pre-tensing. These overall data for greyout incidence are shown in **Fig. 2**.

There was no difference in age between those who still experienced greyout despite pre-tensing (51 ± 17 yr) and those who did not (51 ± 11 yr), and likewise no difference in height, weight, or BMI. When greyout persisted on re-entry, pre-tensing had a significant effect in delaying the onset of visual symptoms [$t(5) = -3.594$, $P = 0.023$], but did not significantly affect the duration of visual symptoms [$t(5) = 2.245$, $P = 0.09$] or the G_x [$t(5) = 0.505$, $P = 0.6$] or G_z [$t(5) = 0.429$, $P = 0.6$] at which symptoms began (**Table I**).

DISCUSSION

G-induced effects on vision and consciousness during suborbital spaceflight have implications both for individuals on board (passengers and crew) and for the wider industry. As regular tourism and research flights expand, regulatory bodies are currently considering future medical policies as part of the broader framework for commercial suborbital operations and are seeking evidence to support the development of medical standards. In this context, this study has confirmed that greyout is common during centrifuge-simulated spaceplane flights and found that anticipatory muscle tensing limited to tensing calves,

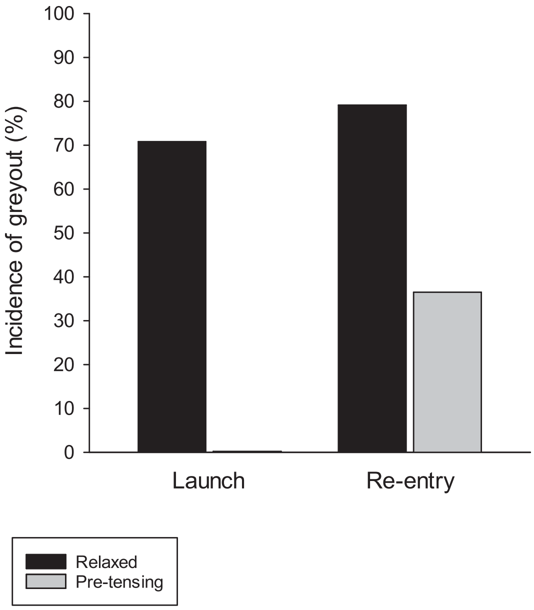

Fig. 2. Overall estimated incidence of greyout. Incidence was determined by applying the preventative effect of pre-tensing observed in the current study to the greyout incidence data from the preceding study.[2] Black columns: greyout when relaxed; grey columns: greyout when pre-tensing.

quadriceps, gluteal, and abdominal muscles prevented greyout completely during the launch phase and partially during re-entry. Muscle tensing was well tolerated and did not cause muscle fatigue, thus this approach appears to offer a relatively simple and effective countermeasure for use by passengers in suborbital spaceplane operations.

In simulated suborbital spaceplane profiles, concurrent $+G_x$ appears to reduce tolerance to $+G_z$ such that visual symptoms develop at lower levels of $+G_z$ than would typically be expected.[2,6,7] It follows that progression to G-LOC may likewise occur more readily, although this has only been reported once, together with one potential episode of almost loss of consciousness (A-LOC) across multiple centrifuge studies comprising several hundred subjects.[2,8] Although the likelihood of G-LOC is low, depending on the actual acceleration profile experienced, it may be higher during actual flights than on a centrifuge, as the transition from microgravity (rather than from 1 G) to high G during re-entry could be associated with a "push-pull effect"-type phenomenon.[9] Obtaining acceleration data together with G-induced effects on vision and consciousness during actual flights are therefore key priorities for research, as this will aid considerations as to whether more robust measures may be required for protecting flight safety critical crew. Another important role for operational data is the determination of factors that may predict or protect against greyout; for example, data from centrifuge studies indicate that the incidence is not associated with sex or baseline blood pressure,[10] although a diagnosis of hypertension may be protective.[5]

This study used the leg and abdominal muscle-tensing component of an AGSM without the breath strain component. Together with anti-G suits, a full AGSM is the mainstay of G protection in military fast jet aviation. G-LOC nevertheless remains an ever-present danger in this setting and G protection and training does not remove the potential for incapacitation even in elite pilots.[6,9] While AGSM can increase G tolerance by 3–4 G_z, poor AGSM performance has been implicated in fast jet accidents and professional aircrew require dedicated centrifuge-based training to perfect the technique.[6,11] This may be relatively unrealistic for members of the public taking suborbital flights, where an improper technique can render the AGSM ineffective as well as causing injury,[5] and a basic "amateur" version is, therefore, appealing. This would ideally be practiced during preflight centrifuge familiarization, which we have previously advocated, and provides further justification for including centrifuge experience in standard preparations for suborbital flights.[2,3]

We found that anticipatory muscle tensing prevented a reasonable proportion of the greyout that occurred during the re-entry phase. The combined $+G_x/+G_z$ peak on re-entry is the most physiologically provocative element of the acceleration profile and is the point at which the episode of G-LOC occurred in our previous study. From our data, the overall incidence of greyout with muscle pre-tensing is approximately 80% during re-entry in a relaxed state, falling to approximately 37% with pre-tensing. This is broadly consistent with a previous report of 15% persistent greyout in laypersons instructed to perform a full AGSM (including breath strain).[5] These results indicate that even with anti-G maneuvers, a minority of individuals will still experience G-related visual symptoms and the potential for G-LOC therefore remains.

Our previous physiology experiments provided evidence that chronological age per se may not be a critical independent factor in adverse effects of suborbital high-G.[2] We, and others, have in fact reported a protective effect of increasing age with respect to greyout in laypersons undertaking suborbital spaceplane profiles,[2,5] although we note that age is not a classic

Table I. Incidence, Onset and Duration of Greyout.

INCIDENCE, ONSET, AND DURATION OF GREYOUT	LAUNCH PHASE		RE-ENTRY PHASE	
	RELAXED	PRE-TENSING	RELAXED	PRE-TENSING
Number of subjects with greyout (*N*)	11	0	13	6
$+G_x$ at onset of greyout (G)	2.4 ± 0.1	–	4.1 ± 0.3	3.9 ± 0.6
$+G_z$ at onset of greyout (G)	3.3 ± 0.5	–	3.7 ± 0.2	3.5 ± 0.4
Time to onset of greyout (s)	12.9 ± 4.1	–	19.8 ± 2.4	22.6 ± 3.7
Duration of greyout (s)	6.3 ± 4.5	–	5.6 ± 3.2	3.4 ± 2.4

Values are mean ± SD.

determinant of G tolerance in the military setting (where the age range is generally narrower). In the current study, the effectiveness of muscle tensing was not related to age and subjects up to 82 yr of age found it easy to perform comfortably. It would, therefore, seem appropriate to employ this technique in all age groups.

With regards to strengths and limitation of this study, the detailed recording of greyout onset and duration across a wide age range is a novel contribution in the suborbital context, and the design minimized potential confounding from an order or learning effect. As in our previous work, the acceleration profile and seating orientation approximated those used operationally and were intended to inform both current and future platforms. As always, it remains possible that a larger sample size and an entirely prospective design would have enabled a stronger dataset.

In summary, greyout is common during simulated spaceplane launch and re-entry in a seated position. Anticipatory pre-tensing of leg and abdominal muscles was effective in preventing greyout completely during the launch phase and partially during re-entry. Anticipatory muscle tensing was well tolerated and feasible, and we recommend its use should be considered as part of routine suborbital spaceplane operations until further data is available. However, even with pre-tensing, a minority of individuals would still be expected to experience greyout, indicating that G-LOC could still occur.

ACKNOWLEDGMENTS

The authors thank the volunteers who took part and the staff of the RAF High G Training and Test Facility, and acknowledge the important contribution of Dr. Stuart Mitchell (former Head of Medical Policy at the CAA) in developing this project.

Financial Disclosure Statement: This work was supported by a grant from the UK Civil Aviation Authority and by in-kind support from the Ministry of Defence and Royal Air Force. The authors have no competing interests to declare.

Authors and Affiliations: Ross D. Pollock, Ph.D., Peter D. Hodkinson, MRCP, Ph.D., and Thomas G. Smith, D.Phil., FRCA, King's College London, London, United Kingdom; Joseph K. Britton, M.B.B.S., D.Av.Med., Nicholas D. C. Green, D.Av.Med., Ph.D., and Daniel Hendriksen, D.Av.Med., MRCGP, Royal Air Force Centre of Aerospace Medicine, RAF Henlow, United Kingdom; and Ryan A. Anderton, D.Av.Med., MRCGP, UK Civil Aviation Authority, Gatwick, United Kingdom.

REFERENCES

1. Smith TG, Buckey JC, Jr. Anaesthetists and aerospace medicine in a new era of human spaceflight. Anaesthesia. 2022; 77(4):384–388.
2. Smith TG, Pollock RD, Britton JK, Green NDC, Hodkinson PD, et al. Physiological effects of centrifuge-simulated suborbital spaceflight. Aerosp Med Hum Perform. 2022; 93(12):830–839.
3. Pollock RD, Jolley CJ, Abid N, Couper JH, Estrada-Petrocelli L, et al. Pulmonary effects of sustained periods of high-G acceleration relevant to suborbital spaceflight. Aerosp Med Hum Perform. 2021; 92(8):633–641.
4. Menden T, Alcain GB, Stevenson AT, Pollock RD, Tank H, et al. Dynamic lung behavior under high G acceleration monitored with electrical impedance tomography. Physiol Meas. 2021; 42(9):094001.
5. Blue RS, Pattarini JM, Reyes DP, Mulcahy RA, Garbino A, et al. Tolerance of centrifuge-simulated suborbital spaceflight by medical condition. Aviat Space Environ Med. 2014; 85(7):721–729.
6. Pollock RD, Hodkinson PD, Smith TG, Oh G. The x, y and z of human physiological responses to acceleration. Exp Physiol. 2021; 106(12):2367–2384.
7. Albery WB. Acceleration in other axes affects +Gz tolerance: dynamic centrifuge simulation of agile flight. Aviat Space Environ Med. 2004; 75(1):1–6.
8. Blue RS, Vardiman JL, Mathers C, Castleberry TL, Vanderploeg JM. Layperson tolerance of centrifuge-simulated suborbital spaceflight: aggregate findings, 2007-2016. [Abstract]. Aerosp Med Hum Perform. 2017; 88(3):231.
9. Metzler MM. G-LOC due to the push-pull effect in a fatal F-16 mishap. Aerosp Med Hum Perform. 2020; 91(1):51–55.
10. Blue RS, Riccitello JM, Tizard J, Hamilton RJ, Vanderploeg JM. Commercial spaceflight participant G-force tolerance during centrifuge-simulated suborbital flight. Aviat Space Environ Med. 2012; 83(10):929–934.
11. Burton RR, Whinnery JE. Operational G-induced loss of consciousness: something old; something new. Aviat Space Environ Med. 1985; 56(8):812–817.