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Gratefulness

Susan Northrup, M.D., M.P.H., FAsMA

As we approach the end of the year, I'd like to reflect on 2022. While we have had to fight the good fight to keep the specialty of Aerospace Medicine intact (and we are prevailing by the way), the bigger field of aviation is starting to rebound across the globe. We played a part in the recovery!

Aeromedical research with people is starting again. Initially the COVID restrictions hampered participants and scientists, but as immunity goes up and cases come down, flight deck human factors research becomes possible. And just in time for the new entrants into aviation. Research will be vital to understanding how the human will interact with Remotely Piloted Aerial Systems and new technology in directly piloted flight decks.

Interest in aviation careers is up! Even in my own state it seems every year there are more vocational aviation programs in the high schools and colleges. In the United States, there was a record number of applications for Airman Medical Certificates—topping 410,000 applications. The biggest growth was in young first-class applicants.

We can meet in person again… Attending both our scientific meeting and ICAM and seeing colleagues and friends was good for my psyche. Meeting people I'd only seen in 2-inch squares on a flat screen was eye opening! Our world is ever more connected because of the pandemic and what we had to do as a profession across the board. But a handshake or hug is priceless. Basic human touch was definitely underrated in 2019.

Recognition of mental health intervention and education is becoming more widespread. Once again, prevention and early recognition are key. There is an international interest and effort underway that will culminate in a Sunday session at AsMA in New Orleans.

Have I mentioned that the AsMA home office staff is incredible and amazing? Seems I have a time or two… But a more dedicated group of people would be hard to find!

So, to sum up, I am very grateful for the organization, my friends and peers I have met through AsMA, and each one of you, our members. I look forward to seeing you in the coming year as we celebrate our efforts and each other.

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Physiological Effects of Centrifuge-Simulated Suborbital Spaceflight

Thomas G. Smith; Ross D. Pollock; Joseph K. Britton; Nicholas D. C. Green; Peter D. Hodkinson; Stuart J. Mitchell; Alec T. Stevenson

BACKGROUND: High-G acceleration experienced during launch and re-entry of suborbital spaceflights may present challenges for older or medically susceptible participants. A detailed understanding of the associated physiological responses would support the development of an evidence-based medical approach to commercial suborbital spaceflight.

METHODS: There were 24 healthy subjects recruited into 'younger' (18-44 yr), 'intermediate' (45-64 yr) and 'older' (65-80 yr) age groups. Cardiovascular and respiratory variables were measured continuously during dynamic combinations of $+G_x$ (chest-to-back) and $+G_z$ (head-to-foot) acceleration that simulated suborbital G profiles for spaceplane and rocket/capsule platforms. Measurements were conducted breathing air and breathing 15% oxygen to simulate a cabin pressure altitude of 8000 ft.

RESULTS: Suborbital G profiles generated highly dynamic changes in heart rate, blood pressure, and cardiac output. G-induced hypoxemia was observed, with minimum arterial oxygen saturation < 80% in a quarter of subjects. Increased age was associated with greater hypoxemia and reduced cardiac output responses but did not have detrimental cardiovascular effects. ECG changes included recurrent G-induced trigeminy in one individual. Respiratory and visual symptoms were common, with 88% of subjects reporting greyout and 29% reporting blackout. There was one episode of G-induced loss of consciousness (G-LOC).

DISCUSSION: Suborbital acceleration profiles are generally well tolerated but are not physiologically inconsequential. Marked hemodynamic effects and transient respiratory compromise could interact with predisposing factors to precipitate adverse cardiopulmonary effects in a minority of participants. Medically susceptible individuals may benefit from expanded preflight centrifuge familiarization that includes targeted physiological evaluation in the form of a 'G challenge test'.

KEYWORDS: passenger health, fitness to fly, spaceflight participant, crew, ageing, +Gx and +Gz acceleration.

Smith TG, Pollock RD, Britton JK, Green NDC, Hodkinson PD, Mitchell SJ, Stevenson AT. *Physiological effects of centrifuge-simulated suborbital spaceflight*. Aerosp Med Hum Perform. 2022; 93(12):830–839.

Foundational knowledge of the physiological effects of commercial airline flights underpins the process of assessing and optimizing airline passenger fitness-to-fly and thereby facilitating safe travel.[12,24] Commercial suborbital spaceflights are now available for tourism and scientific research, and are ultimately anticipated to mature into extremely fast point-to-point travel (e.g., London-Sydney in less than 2 h).[22] Just as for air travel, a strong foundational knowledge of fundamental flight-related physiology is required to inform medical decision-making and maximize safe access to suborbital flights.

Stressors of suborbital spaceflight can include mild hypoxia from airline-style cabin pressure altitudes of 6000–8000 ft (1829–2438 m),[23,25,29] but also extend beyond the air travel paradigm to include dynamic high-G and zero G exposures. Flight profiles vary in detail and are specific to each platform

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but include a high-G launch phase followed by a period of microgravity and then a further high-G phase during atmospheric re-entry.[1] Physiological challenges associated with this environment may well be clinically relevant for a small subset of suborbital spaceflight participants, who more typically resemble airline passengers than professional astronauts or flight crew with respect to background health and fitness.[3,6,22] At least initially, suborbital participants are also more likely to come from older age groups, with a naturally higher prevalence of medical disease,[6] and ageing-related physiological changes could additionally contribute to the development of flight-related complications.

The high-G phases of suborbital flight combine variable degrees of $+G_x$ (chest-to-back) and $+G_z$ (head-to-foot) acceleration that depend on several factors including the spacecraft and launch platform, the flight trajectory and the orientation of the seat (upright or reclined). Suborbital $+G_x$ loads can exceed $+3\ G_x$ for periods of 20–30 s and peak at up to $+6\ G_x$ on re-entry, while $+G_z$ may exceed $+3\ G_z$ for similar periods and peak at up to $+4\ G_z$.[1,4,7]

Large centrifuge-based studies have simulated suborbital spaceplane profiles in volunteers across a wide range of ages and with multiple well-controlled medical conditions, and have established that these profiles are likely to be tolerable for the majority of participants.[5,7,8] However, in these studies approximately 5% of volunteers were unable to complete the G exposures, and transient physical symptoms were not uncommon.[6] Visual G symptoms were frequently reported,[7] and while there have been no reports of G-induced loss of consciousness (G-LOC), across several studies comprising 314 subjects there was one potential episode of almost loss of consciousness (A-LOC).[9] Several asymptomatic arrythmias were triggered by the G profiles including bigeminy, accelerated idioventricular rhythm and a short run of ventricular tachycardia, and the investigators advised that heightened caution is warranted in individuals with cardiopulmonary disease or taking cardiac medications.[27]

Our recent work has focused on the pulmonary response to extended periods of static $+G_x$ over the suborbital range, allowing detailed characterization of the underlying physiological response to relevant G loads up to $+6\ G_x$.[17,20] Increasing $+G_x$ caused substantial changes in respiratory function and progressive hypoxemia that was exacerbated by a simulated cabin pressure altitude of 8000 ft, and was accompanied by breathlessness and musculoskeletal chest pain at higher levels of $+G_x$.[17,20]

Suborbital flights will evoke these and other underlying responses to some extent, and could potentially interact with predisposing factors to precipitate detrimental sequelae. This prospect has obvious clinical implications for individual participants but also has broader implications for the industry. Regulatory bodies are currently considering the future framework for suborbital operations including the medical approach to flight crew and to prospective participants, and there is current military interest in developing a future suborbital medevac capability allowing extremely rapid repatriation of casualties. Together with the expansion of regular tourism and research flights, there is a growing requirement to establish how suborbital acceleration profiles affect the body. This physiology study aimed to generate boundary data relevant to both current and future suborbital platforms using representative acceleration profiles. We aimed to determine what physiological changes occur in response to simulated suborbital acceleration profiles, including the effect of simulated airline-style cabin pressurization, and additionally investigated how these responses are affected by age.

METHODS

Subjects

There were 24 healthy volunteers recruited in three age brackets: a 'younger' group aged 18–44 yr, an 'intermediate' group aged 45–64 yr, and an 'older' group aged 65–80 yr. Subject and group characteristics are shown in **Table I**. Subjects were required to be in good health, as evidenced by holding a UK Civil Aviation Authority (CAA) Class 2 Medical Certificate (as a minimum), which is the medical standard required for private pilots in the UK and includes an electrocardiogram (ECG). Subject recruitment therefore targeted pilots holding the requisite medical certificate who had an interest in commercial spaceflight or high-performance flying. Pregnancy and BMI > $35\ kg \cdot m^{-2}$ were additional exclusion criteria, and to satisfy relevant RAF standards subjects confirmed specifically that they did not have major cardiac or respiratory disease, significant back or neck pathology, retinal detachment or untreated hernias. 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 using a 7.5-m radius centrifuge at the Royal Air Force High G Training and Test Facility (RAF Cranwell, UK) with a representative F-35 Lightning cockpit installed in the gondola (seatback angle 22°). Acceleration was measured at head level in all axes. Subjects wore a Type P/Q military aircrew oxygen mask modified with a gas sampling port, from which oxygen and carbon dioxide were measured using an O_2Cap oxygen/CO_2 analyzer (Oxigraf Inc., Sunnyvale, CA, USA). Breathing gas was supplied via an Mk17F panel-mounted aircraft oxygen regulator with an inline flow transducer, and could be switched between air and 15% oxygen (balance 85% nitrogen) to simulate a cabin pressure altitude of 8000 ft (2438 m). Heart-level blood pressure was measured continuously using an NIBP Nano (AD Instruments, Oxford, UK) applied to a finger of the right hand, which was positioned at the side of the chest at heart level using a sling, and cardiac output was derived from the arterial pressure waveform using integrated pulse wave analysis.[16] Subjects held a marker button in the left hand and pressed this to indicate the onset of any visual G symptoms. Three-lead ECG, arterial oxygen saturation (S_pO_2),

Table I. Subject and Group Characteristics.

CHARACTERISTICS	YOUNGER GROUP	INTERMEDIATE GROUP	OLDER GROUP	ALL SUBJECTS COMBINED
N	8	8	8	24
Male:Female	5:3	5:3	6:2	16:8
Age (yr)	37 ± 5 (32–43)	55 ± 5 (49–63)	69 ± 5 (65–80)	54 ± 14 (32–80)
Weight (kg)	74 ± 12 (57–94)	80 ± 15 (56–98)	74 ± 18 (44–97)	76 ± 15 (44–98)
Height (m)	1.74 ± 0.09 (1.60–1.88)	1.75 ± 0.10 (1.57–1.85)	1.74 ± 0.10 (1.58–1.88)	1.74 ± 0.09 (1.57–1.88)
BMI	24.2 ± 2.4 (22.3–29.1)	26.2 ± 4.2 (20.6–32.6)	24.0 ± 4.3 (17.6–29.9)	24.8 ± 3.7 (17.6–32.7)
FEV_1 (l)	4.18 ± 0.68	3.50 ± 0.64	3.11 ± 0.67	3.59 ± 0.78
(FEV_1% Predicted)	(106 ± 9)	(102 ± 11)	(104 ± 15)	(104 ± 12)
FVC (l)	4.91 ± 0.82	4.37 ± 0.90	3.88 ± 0.79	4.39 ± 0.91
(FVC % Predicted)	(101 ± 9)	(100 ± 11)	(98 ± 10)	(100 ± 10)
Previous Experience of $+G_z$ on a Centrifuge	7 (88%)	1 (13%)	3 (38%)	11 (46%)
Previous Experience of $+G_z$ in an Aircraft	5 (63%)	5 (63%)	7 (88%)	17 (71%)

FEV_1: forced expiratory volume in the first second. FVC: forced vital capacity. Mean ± SD values and range are shown.

tidal volume and respiratory rate, breath-by-breath end-tidal partial pressures of oxygen ($P_{ET}O_2$) and carbon dioxide ($P_{ET}CO_2$), and beat-by-beat blood pressure were recorded continuously via PowerLab and LabChart 8 (AD Instruments, Oxford, UK).

Procedure

Centrifuge-naïve subjects received a familiarization session prior to the experimental day that included suborbital profiles of reduced magnitude and duration and one complete suborbital profile. All subjects were briefed on what to expect throughout the study, including the potential for partial visual loss (greyout) and complete visual loss (blackout). Subjects did not wear anti-G trousers or other G-protection and were instructed to remain relaxed in the absence of visual symptoms, and to perform leg muscle tensing and press the marker button immediately if greyout developed. Leg muscle tensing consisted of pushing down on the rudder pedals while tensing the leg muscles to clear vision. Subjects were not instructed in any other anti-G measures, and formal anti-G straining maneuvers were not part of the study.

Subjects undertook three different G profiles that were intended to be representative and relevant to current and future suborbital operations. The profiles were based on publicly available information[4,7] and accounted for seatback angles, and are shown in **Fig. 1**, **Fig. 2**, and **Fig. 3** together with the main results. All $+G_z$ and $+G_x$ values were relative to the subject axis. Two profiles represented an air-launched spaceplane, with a common launch phase in an upright seated position (seatback angle of 20° from vertical, 'head level' peak $+G_z$ 3.7, peak $+G_x$ 3.6) and re-entry in either a reclined (seatback angle 70°, peak $+G_z$ 1.2, peak $+G_x$ 5.9) or upright seated position (seatback angle 20°, peak $+G_z$ 4.0, peak $+G_x$ 4.5). A third profile represented a vertical rocket-launched capsule flight with both launch and re-entry in a recumbent position (seatback angle 70°, peak $+G_z$ 2.7, peak $+G_x$ 4.2). Between the high-G launch and re-entry phases $+G_x$ was off-loaded for approximately 30 s.

Profiles were undertaken twice, once breathing air and once breathing 15% oxygen, and subjects were blinded to the gas mixture. The order of the G profiles and gas mixtures was counterbalanced. There was a 5-min wash-in period when the gas mixture was changed, and exposures were separated by a minimum of 2 min at centrifuge baseline G level (+1.2 G_z). Normalization of physiology was confirmed before proceeding with each profile. Breathlessness intensity was recorded after each individual profile using the modified Borg (mBorg) scale,[10] and subjective data were captured using a symptom questionnaire.

Statistical Analysis

A repeated measure mixed model approach with Greenhouse-Geisser correction was used to analyze the effect of age and the effect of breathing 15% oxygen on physiological responses (GraphPad Prism 9.3.1). A Mann-Whitney U Test was used to compare the ages of subjects who did and did not experience visual symptoms. Statistical significance was assumed at $P < 0.05$. Data are reported as mean ± SEM unless otherwise stated.

RESULTS

There were 24 subjects (16 men, 8 women) with 8 in each age group. The overall age range was 32–80 yr. Subject and group characteristics are shown in Table I. The groups were well matched for body habitus and spirometry was normal across the groups. Most subjects had some prior experience of $+G_z$ (Table I). Several medical conditions were declared, particularly by the older subjects, and these are shown in **Table II**. All were well controlled in accordance with the CAA Class 2 Medical Certificate standard. Acceleration profiles (Fig. 1–3) were well tolerated overall, and all subjects completed all G exposures with the exception of one profile that was terminated shortly after peak G due to G-LOC.

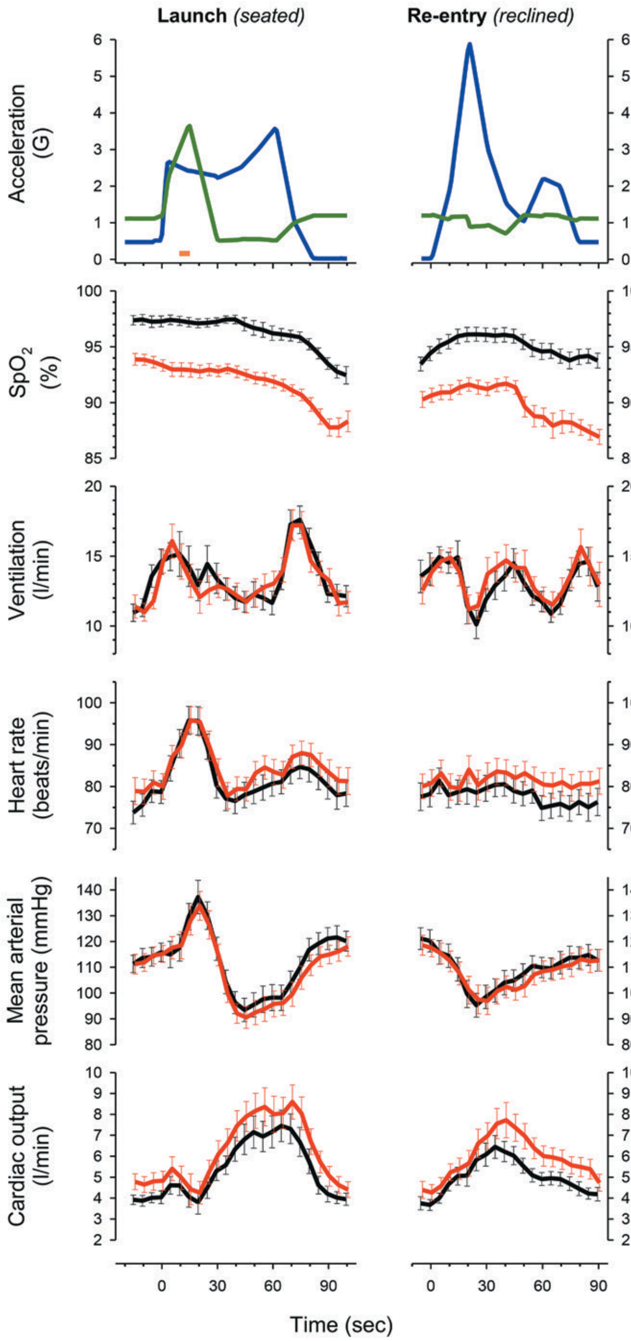

Fig. 1. Physiological responses to a simulated spaceplane profile with re-entry in a reclined position. The data shown are applied acceleration, arterial oxygen saturation (S_pO_2), ventilation, heart rate, mean arterial blood pressure measured at heart level, and cardiac output. The range over which the onset of visual G symptoms occurred is indicated with an orange bar on the acceleration profiles. Left panels show launch phase data and right panels show re-entry phase data. Data were obtained while breathing air and breathing 15% oxygen to simulate a cabin pressure altitude of 8000 ft. Data are mean ± SEM. Blue lines: $+G_x$; green lines: $+G_z$; black lines: breathing air; red lines: breathing 15% O_2.

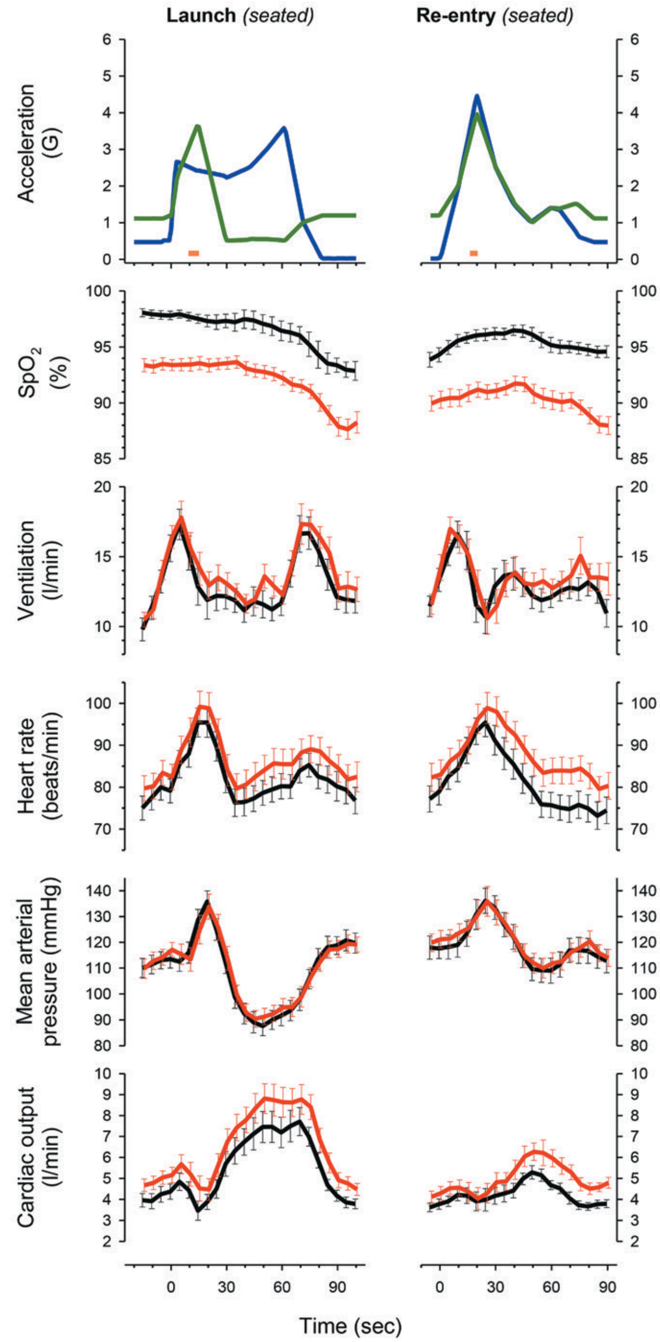

Fig. 2. Physiological responses to a simulated spaceplane profile with re-entry in an upright seated position. The data shown are applied acceleration, arterial oxygen saturation (S_pO_2), ventilation, heart rate, mean arterial blood pressure measured at heart level, and cardiac output. The range over which the onset of visual G symptoms occurred is indicated with an orange bar on the acceleration profiles. Left panels show launch phase data and right panels show re-entry phase data. Data were obtained while breathing air and breathing 15% oxygen to simulate a cabin pressure altitude of 8000 ft. Data are mean ± SEM. Blue lines: $+G_x$; green lines: $+G_z$; black lines: breathing air; red lines: breathing 15% O_2.

Symptom questionnaire data and mBorg breathlessness scores are shown in **Table III**. Approximately two-thirds of subjects reported transient chest heaviness that was 'unpleasant' and difficulty breathing. This was typically under peak $+G_x$, which also generated a sensation of throat 'constriction' obstructing airflow in two older subjects. Breathlessness was greatest during reclined spaceplane re-entry, when the highest magnitude of $+G_x$ was experienced, with a median mBorg score of 4 ('somewhat severe breathlessness') and a maximum of 5 ('severe breathlessness'). Nausea and occasional vomiting

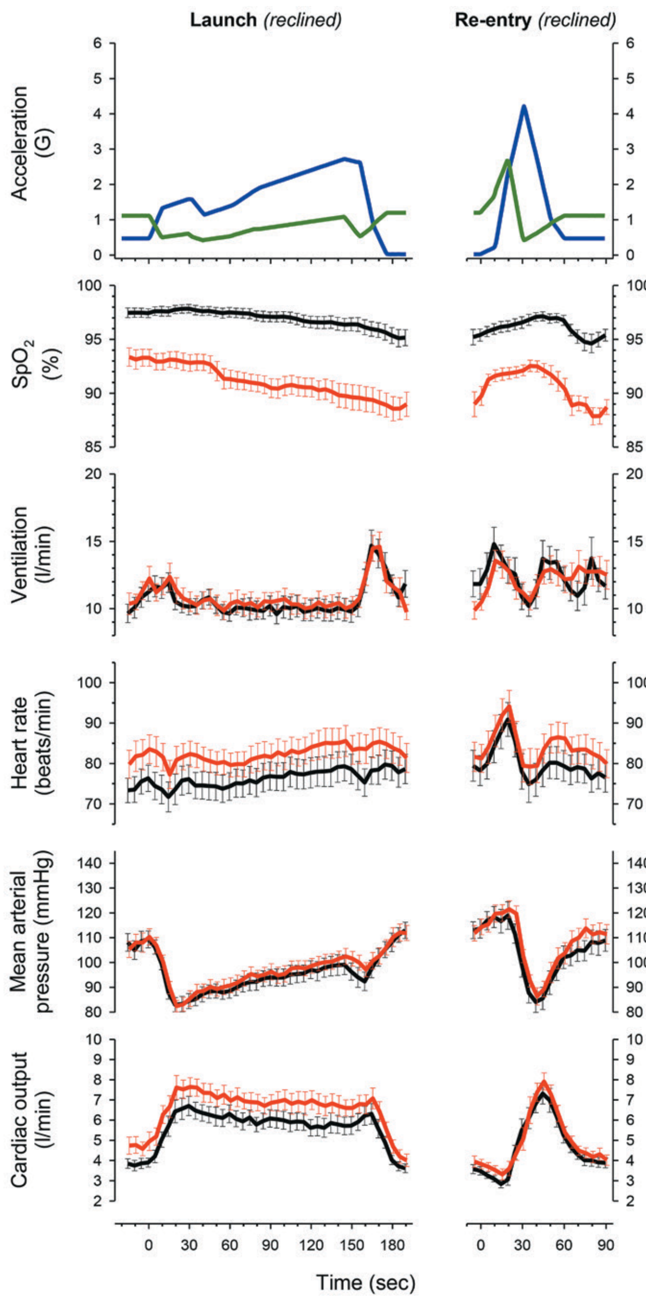

Fig. 3. Physiological responses to a vertical rocket-launched capsule profile with launch and re-entry in a recumbent position. The data shown are applied acceleration, arterial oxygen saturation (S_pO_2), ventilation, heart rate, mean arterial blood pressure measured at heart level, and cardiac output. Left panels show launch phase data and right panels show re-entry phase data. Data were obtained while breathing air and breathing 15% oxygen to simulate a cabin pressure altitude of 8000 ft. Data are mean ± SEM. Blue lines: $+G_x$; green lines: $+G_z$; black lines: breathing air; red lines: breathing 15% O_2.

(Table III) were attributed to rotational acceleration on a centrifuge and are not necessarily translatable to suborbital flight.

A large proportion of subjects experienced visual symptoms at least once, with 88% reporting greyout and 29% reporting blackout. Apart from one greyout during vertical rocket launch, all visual symptoms occurred during upright seated spaceplane phases which involved greater $+G_z$ exposures. During spaceplane launch the incidence of visual symptoms was 67% (N = 16) breathing air and 58% (N = 14) breathing reduced oxygen. During spaceplane re-entry in a seated position the incidence was 71% breathing air (N = 17) and 63% breathing reduced oxygen (N = 15). Visual symptoms occurred within a tight range of $+G_z$ and $+G_x$ which is indicated on Fig. 1 and Fig. 2. The G threshold for visual symptoms was effectively identical whether breathing air or 15% oxygen, as shown in **Fig. S1** in the supplementary online **Appendix A** (https://doi.org/10.3357/AMHP.6153sd.2022). Those who experienced visual symptoms [mean age 50 ± 14 yr (SD)] were significantly younger than those who did not (66 ± 6 yr; U = 81, P = 0.015). There was one episode of G-LOC which occurred during the profile simulating spaceplane re-entry in an upright seated position while breathing 15% oxygen. The subject was an 80-yr-old man who noted afterwards that he had been concentrating on indicating the onset of visual symptoms with the marker button and, distracted by this, had then forgotten to perform muscle tensing. Greyout coincided with the combined $+G_x/+G_z$ re-entry peak and G-LOC occurred 9 s later. S_pO_2 was 86% at the time, and momentary breath-holding at peak G was observed.

Fig. 1, Fig. 2, and Fig. 3 show continuous data for S_pO_2, ventilation, heart rate, heart-level mean arterial blood pressure and cardiac output for the three respective suborbital profiles. Data are shown breathing air and breathing 15% oxygen. Peak physiological changes from baseline are quantified in **Table IV** for each age group. A fall in S_pO_2 was observed with all G exposures (Fig. 1**,** Fig. 2, and Fig. 3) and was more pronounced when simulating spaceplane profiles. The minimum S_pO_2 for each phase of each profile is shown in **Fig. 4**. Minimum values tended to cluster around 89–94% breathing air and 83–88% breathing reduced oxygen, but there were numerous outlying values below these ranges, and six subjects (including at least one from each age group) desaturated to an S_pO_2 value < 80% at some point. Ventilation appeared to be restricted during periods of $+G_x$, with subsequent recovery and overshoot as $+G_x$ returned to baseline demonstrated most clearly in Fig. 3. Respiratory rate and tidal volume data corroborated this and are shown in **Fig. S2, Fig. S3,** and **Fig. S4** in the supplementary online appendix (https://doi.org/10.3357/AMHP.6153sd.2022) together with $P_{ET}O_2$ and $P_{ET}CO_2$, which illustrated real-time impairment of ventilation/perfusion matching as they rose ($P_{ET}O_2$) and fell ($P_{ET}CO_2$), respectively, with high G.

Marked hemodynamic changes were observed during all three profiles. These were most pronounced during the upright seated launch phase, which was common to both spaceplane profiles and produced the same responses in both (Fig. 1 and Fig. 2). The initial $+G_z$ peak was associated with a rapid elevation in heart rate and blood pressure, then as the $+G_z$ reduced and $+G_x$ continued to build, heart rate returned toward baseline while blood pressure swung low, falling approximately 50 mmHg from its peak, alongside a large rebound increase in cardiac output. Cardiovascular responses to spaceplane re-entry in a seated position (Fig. 2) were somewhat similar although smaller in magnitude. The combined $+G_x/+G_z$ peak was associated with increases in heart rate and blood pressure, which were

Table II. Medical History of Subjects.

	YOUNGER GROUP	INTERMEDIATE GROUP	OLDER GROUP
Declared Medical Conditions	Hyperlipidemia	Hypertension	Hypercholesterolaemia (*N* = 4) Hypertension (*N* = 2) Gastro-esophageal reflux disease Mild coronary artery disease Prostate cancer Hypothyroidism
Regular Medications	Atorvastatin, fenofibrate	Amlodipine, lisinopril	Antihypertensives: ramipril, amlodipine, losartan Statins: pravastatin, lansoprazole Other: thyroxine, enzalutamide, aspirin

followed by a smaller post-G increase in cardiac output. Spaceplane re-entry in a reclined position caused less cardiovascular disturbance, although cardiac output was elevated during the $+G_x$ peak (Fig. 1). During vertical rocket launch (Fig. 3), offloading $+G_z$ together with increasing $+G_x$ was associated with a fall in blood pressure and increase in cardiac output, while the adjacent $+G_z$ and $+G_x$ peaks of capsule re-entry were accompanied by a rise in heart rate, a decrease in blood pressure and a corresponding increase in cardiac output. Premature atrial and ventricular complexes are common during high-G acceleration[19] and were frequently observed on ECG monitoring during all profiles, although G-related ectopy was much more common in the older age groups. One individual, a 67-yr-old man with no cardiac history, developed asymptomatic trigeminy that occurred consistently at peak G, lasting up to 40 s before reverting to sinus rhythm. The ECG rhythm strip showing trigeminy under G is reproduced in **Fig. S5** in the supplementary online Appendix A (https://doi.org/10.3357/AMHP.6153sd.2022).

Figs. S6, S7, and S8 in the supplementary online Appendix A (https://doi.org/10.3357/AMHP.6153sd.2022) show the continuous physiological data presented in Fig. 1, Fig. 2, and Fig. 3, but separated into the three respective age groups. There was a significant effect of age on S_pO_2, which was lowest in the older group [$F(2, 21) = 4.192$, $P = 0.029$]. There was also a significant effect of age on cardiac output [$F(2, 21) = 12.08$, $P < 0.001$]; taking the study as a whole, the increase in cardiac output during G profiles in the older group was approximately half that of the younger group, with the intermediate age group in between. There was no effect of age on ventilation [$F(2, 21) = 0.2$, $P = 0.8$], heart rate [$F(2, 21) = 0.1677$, $P = 0.8$], or blood pressure [$F(2, 20) = 0.9509$, $P = 0.4$]. Compared with breathing air, breathing 15% oxygen caused a decrease in S_pO_2 [$F(1, 46) = 76.60$, $P < 0.001$] as shown in Fig. 1, Fig. 2, and Fig. 3, but did not affect ventilation [$F(1, 46) = 0.1535$, $P = 0.7$], heart rate [$F(1, 46) = 1.317$, $P = 0.3$], blood pressure [$F(1, 46) < 0.001$, $P = 0.99$], or cardiac output [$F(1, 46) = 2.549$, $P = 0.1$].

Table III. Questionnaire Data and mBorg Breathlessness Scores.

	YOUNGER GROUP	INTERMEDIATE GROUP	OLDER GROUP	ALL SUBJECTS COMBINED
Symptoms Associated with G Profiles				
Greyout	8 (100%)	8 (100%)	5 (63%)	21 (88%)
Blackout	3 (38%)	2 (25%)	2 (25%)	7 (29%)
G-LOC	0	0	1 (13%)	1 (4%)
Presyncope or light-headedness	1 (13%)	2 (25%)	0	3 (38%)
Difficulty breathing	7 (88%)	5 (63%)	3 (38%)	15 (63%)
Unpleasant chest 'heaviness'	8 (100%)	6 (75%)	2 (25%)	16 (67%)
Throat 'constriction' at peak $+G_x$	0	0	2 (25%)	2 (8%)
Disorientation or vertigo	3 (38%)	3 (38%)	2 (25%)	8 (33%)
Nausea	2 (25%)	3 (38%)	4 (50%)	9 (38%)
Vomiting	1 (13%)	0	1 (13%)	2 (8%)
Palpitations	0	0	2 (25%)	2 (8%)
Modified Borg Breathlessness Scores				
Baseline Air	0 (0–0)	0 (0–0)	0 (0–0.5)	0 (0–0.5)
Hypoxia	0 (0–0.5)	0 (0–0.5)	0 (0–0.5)	0 (0–0.5)
Spaceplane profile (reclined re-entry) Air	4.5 (3–5)	5 (3.5–5)	2 (1–3.5)	4 (2–5)
Hypoxia	4 (4–4.5)	4 (3.5–4.5)	2 (1.5–3.5)	4 (2–4.5)
Spaceplane profile (seated re-entry) Air	3 (2–4.5)	3 (2.5–4)	1.5 (0.5–2.5)	3 (1–3.5)
Hypoxia	4 (2–4)	4 (3.5–4)	2 (1–3)	3 (2–4)
Capsule flight profile Air	2.5 (2–4)	3 (2–4)	1 (0–2.5)	2 (1–4)
Hypoxia	2.5 (1–4)	3 (2.5–4)	1 (1–2.5)	3 (1–4)

Number of subjects and percentage are shown. For modified Borg scores, median (IQR) is shown. Scores recorded while breathing 15% oxygen are denoted as Hypoxia. The mBorg scale runs from 0–10, where 0 is no breathlessness at all and 10 is the maximum severity of breathlessness imaginable. An mBorg score of 5 indicates 'Severe breathlessness'.

Table IV. Peak Changes in Main Physiological Variables During Simulated Suborbital Flights.

		SIMULATED SPACEPLANE FLIGHT WITH RE-ENTRY IN RECLINED POSITION		SIMULATED SPACEPLANE FLIGHT WITH RE-ENTRY IN SEATED POSITION		SIMULATED CAPSULE FLIGHT	
		LAUNCH	RE-ENTRY	LAUNCH	RE-ENTRY	LAUNCH	RE-ENTRY
Minimum S_pO_2(%)							
Younger Group	Air	93 ± 4	94 ± 3	93 ± 3	94 ± 2	96 ± 2	95 ± 2
	Hypoxia	86 ± 3	85 ± 4	86 ± 4	83 ± 3	91 ± 3	87 ± 4
Intermediate Group	Air	91 ± 3	91 ± 3	88 ± 7	91 ± 3	94 ± 2	92 ± 3
	Hypoxia	86 ± 3	84 ± 1	87 ± 4	86 ± 4	86 ± 5	85 ± 5
Older Group	Air	90 ± 4	91 ± 3	90 ± 4	92 ± 3	93 ± 5	93 ± 5
	Hypoxia	83 ± 5	82 ± 6	82 ± 5	82 ± 5	84 ± 7	84 ± 4
Maximal increase in heart rate (bpm)							
Younger Group	Air	32 ± 10	9 ± 5	29 ± 7	24 ± 10	13 ± 11	20 ± 5
	Hypoxia	28 ± 7	11 ± 4	28 ± 10	25 ± 11	10 ± 5	20 ± 3
Intermediate Group	Air	21 ± 8	11 ± 7	22 ± 6	19 ± 11	11 ± 5	12 ± 3
	Hypoxia	19 ± 7	10 ± 6	22 ± 8	17 ± 7	8 ± 5	14 ± 7
Older Group	Air	16 ± 4	9 ± 5	13 ± 4	16 ± 7	11 ± 8	9 ± 4
	Hypoxia	14 ± 5	12 ± 7	17 ± 5	17 ± 7	12 ± 9	10 ± 2
Maximal decrease in mean arterial blood pressure (mmHg)							
Younger Group	Air	21 ± 8	33 ± 9	24 ± 11	12 ± 8	30 ± 10	31 ± 8
	Hypoxia	20 ± 11	20 ± 11	21 ± 12	16 ± 7	26 ± 8	21 ± 8
Intermediate Group	Air	28 ± 9	32 ± 14	26 ± 10	20 ± 4	21 ± 11	32 ± 7
	Hypoxia	32 ± 11	34 ± 12	29 ± 6	17 ± 6	20 ± 12	25 ± 6
Older Group	Air	21 ± 10	32 ± 21	31 ± 16	9 ± 6	23 ± 9	21 ± 7
	Hypoxia	21 ± 15	33 ± 16	26 ± 7	12 ± 9	31 ± 10	33 ± 10
Maximal increase in cardiac output ($L \cdot min^{-1}$)							
Younger Group	Air	6.0 ± 1.9	3.3 ± 1.1	6.3 ± 2.4	2.3 ± 2.5	4.0 ± 1.1	4.5 ± 1.2
	Hypoxia	6.5 ± 2.7	4.6 ± 3.6	6.5 ± 1.7	3.7 ± 2.8	4.7 ± 1.6	4.3 ± 1.6
Intermediate Group	Air	5.1 ± 2.6	3.7 ± 2.8	4.0 ± 2.3	1.7 ± 0.8	3.8 ± 1.1	4.0 ± 1.8
	Hypoxia	5.1 ± 2.9	4.5 ± 2.4	4.9 ± 1.7	1.8 ± 1.0	3.3 ± 1.3	3.7 ± 1.3
Older Group	Air	2.2 ± 1.8	1.9 ± 1.1	2.8 ± 0.6	1.5 ± 0.4	2.0 ± 0.6	2.3 ± 0.6
	Hypoxia	2.9 ± 2.4	3.0 ± 2.5	3.1 ± 0.6	1.2 ± 0.5	3.0 ± 0.4	3.7 ± 1.0

Maximal changes from baseline are shown for cardiovascular variables. Values are mean ± SD.

DISCUSSION

Commercial human suborbital spaceflight has opened a new frontier within aerospace medicine, and current understanding of the associated physiology remains limited.[3] This study provides a detailed description of physiological responses to simulated suborbital launch and re-entry, and has established that previously described respiratory effects[17,20] result in frequent symptoms and occasionally profound hypoxemia during these profiles. It has further demonstrated highly dynamic cardiovascular responses with recurring greyout and frequent blackout during simulated spaceplane profiles, and the episode of G-LOC we observed is, to our knowledge, the first reported in the suborbital context.

'G-tolerance' is defined as the ability to withstand a certain level of $+G_z$, most commonly in the context of visual loss, and is a crucial concept for military fast jet aircrew and for pilots of civilian high-performance aircraft.[19] Deliberate application of simultaneous $+G_x$ is unusual in these settings, but static addition of +2.5 G_x has been shown to reduce relaxed G-tolerance by approximately 0.25 G.[2] Suborbital spaceplane flights dynamically combine significant $+G_x$ and $+G_z$, and during representative simulated profiles we found that visual symptoms developed at lower levels of $+G_z$ than would typically be expected for pure $+G_z$ exposures,[19] consistent with impairment of G-tolerance by concurrent $+G_x$. The overall incidence of greyout was very high and more than a quarter of subjects experienced blackout. These results compare with a greyout rate of 69% in a previous centrifuge-based suborbital study, which also reported a protective effect of increasing age.[7] We likewise found that the small number of subjects who did not experience visual symptoms were significantly older than those who did. This is in contrast to the military $+G_z$ experience, where age is not a classic determinant of G tolerance, and we note that the single episode of G-LOC was in the oldest subject. The episode occurred during simulated spaceplane re-entry in an upright seated position while breathing 15% oxygen. A possible contribution from the simulated cabin conditions cannot be excluded, although S_pO_2 was not precipitously low at the time, and subconscious breath-holding under peak G may be a more likely factor. The subject attributed the G-LOC to his age, stating that he was confident his younger self would not have forgotten to perform leg muscle tensing, raising the question of what role nonphysiological aspects of ageing may play in responses to suborbital flight. A single case does not allow definitive etiological conclusions, but this episode does establish that G-LOC can occur during simulated suborbital G profiles. In doing so it also highlights the need for appropriately tailored

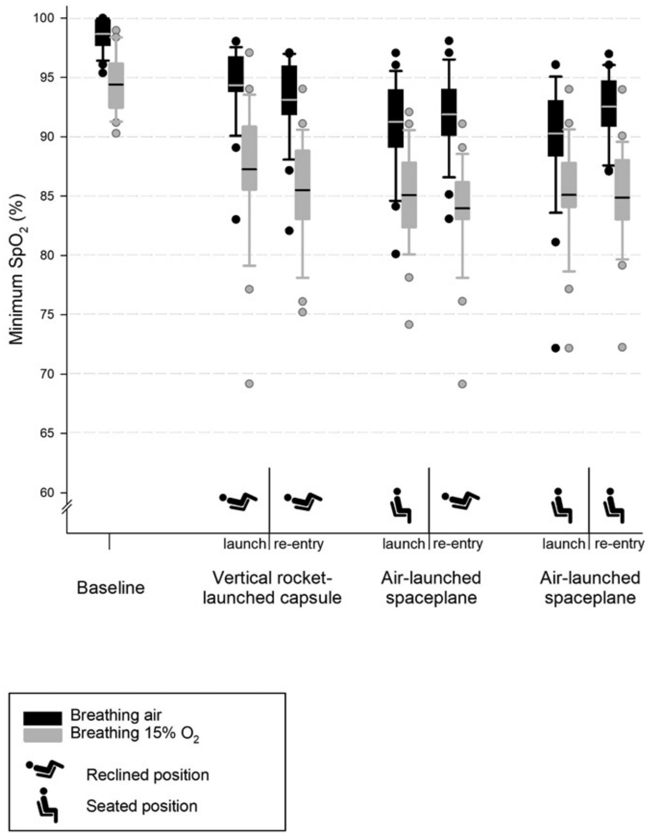

Fig. 4. Minimum arterial oxygen saturation during suborbital acceleration profiles. The minimum arterial oxygen saturation (S_pO_2) measured during each launch and re-entry phase of each suborbital profile is shown, including the mean (bar inside boxes), interquartile range (boxes), 10–90% range (whiskers) and individual outliers beyond this range (circles). Data were obtained while breathing air (black symbols) and breathing 15% oxygen to simulate a cabin pressure altitude of 8000 ft (gray symbols).

assessment and training to minimize the likelihood of G-LOC, which could be higher on actual flights due to a 'push-pull effect'-type phenomenon associated with transition from 0 G (rather than from 1 G) to high-G on re-entry.[18]

Visual G symptoms and G-LOC are closely linked to the underlying physiological responses that this study sought to characterize. The large hemodynamic fluctuations seen during upright seated spaceplane phases appeared to be driven primarily by $+G_z$, with reflex increases in heart rate and heart-level blood pressure attempting to maintain cerebral perfusion in the face of direct hydrostatic effects, dependent arteriolar distension and venous pooling, and reduced venous return.[19] As $+G_z$ eased, the presence of significant $+G_x$ appeared to amplify the recovery of venous return and cause a large rebound increase in cardiac output, possibly accentuated by the relative 'legs up' posture of a reclined seat. Although striking, this large surge in cardiac output reflects the confluence of fundamental cardiovascular processes playing out, rather than a specific protective response, and the fact that it was significantly lower in the older group is not necessarily of concern. This difference probably arises from age-related vascular stiffening and changes in peripheral vascular resistance,[15] with possible contributions from attenuation of cardiac contractility and autonomic function.[13] Age also affected S_pO_2, consistent with age-related deterioration in gas exchange,[28] but there were no other significant effects of age on physiological responses, and it is possible that chronological age per se may be less critical in suborbital fitness-to-fly considerations than previously thought.[20,22]

The current respiratory data extend our previous findings from static $+G_x$ exposures to confirm that impairment of gas exchange and consequent oxygen desaturation routinely develop to some degree during simulated suborbital profiles. We have previously established during $+G_x$ that this is caused by progressive G-dependent ventilation/perfusion mismatching alongside reversal in the relative distribution of regional lung ventilation, anterior gas trapping, increased work of breathing and neural respiratory drive, and limitation of ventilatory responses by impaired pulmonary mechanics (neuroventilatory uncoupling).[17,20] Overlaying mild hypoxia to simulate a cabin pressure altitude of 8000 ft unsurprisingly exacerbated the hypoxaemia associated with suborbital acceleration, but had no other effects. It is reassuring that, in the presence high G acceleration and its predominating responses, this additional reduction in arterial oxygenation is apparently insufficient to stimulate further effects on cardiopulmonary responses or visual symptom thresholds. On average, the fall in S_pO_2 during suborbital profiles was mild-moderate and well tolerated, and would not be concerning for the majority of participants. However, with outlying values in the 69–75% range, coupled with frequently reported respiratory symptoms, it is conceivable that susceptible individuals with pre-existing deficits in lung function could develop clinically meaningful effects. Transient sensations of chest heaviness, difficulty breathing and breathlessness during peak $+G_x$ were common and could be worse in those with pre-existing morbidity such as obesity or cardiopulmonary pathology, in whom greater hypoxemia may develop, increasing the risk of rare complications such as parenchymal lung damage, myocardial infarction, or serious arrhythmias.[11,27,30]

The arrhythmogenic potential of high/zero/high-G suborbital flight profiles is important because, although no doubt unlikely, an aberrant rhythm occurring in-flight could result in significant morbidity or even mortality. We observed repeated G-induced trigeminy in one individual, adding to the short list of rhythm disturbances that have been documented during suborbital G profiles.[27] None of these were associated with apparent hemodynamic compromise or adverse sequelae, and the propensity for benign ECG changes during centrifuge acceleration is well known.[19] Nevertheless, considering the rapidity and amplitude of the dynamic cardiovascular changes observed in this study, and the prevalence of diagnosed and undiagnosed cardiac pathology in the population, the latent risk of triggering a malignant rhythm is presumably not zero. Indeed, such swings in vital signs would be undesirable in clinical contexts such as anesthesia and critical care, where hemodynamic instability and coexisting hypoxia can be proarrhythmic and are considered best avoided.[22] The microgravity phase of actual suborbital flights could also interact with high-G and further challenge cardiopulmonary homeostasis. Transition to microgravity causes increased cardiac sphericity and changes the pressure/volume relationship, with decreased central venous pressure but increased left ventricular volume and cardiac output.[14] Whether this is problematic for older people with 'stiff' hearts is unknown, and in-flight studies are required to determine whether sudden transition from microgravity (rather than from 1 G) to hypergravity on re-entry intensifies the physiological effects sufficiently to cause concern.

Based on our findings, we believe routine preflight centrifuge familiarization, which is not currently mandated,[26] would be highly beneficial for prospective suborbital participants, providing helpful preparation for the physical and psychological challenges of high-G acceleration rather than experiencing these for the first time on an actual spaceflight. With the addition of appropriate monitoring, this centrifuge experience could also be tailored to allow relevant physiological assessment, and we suggest consideration of such a 'G challenge test' in medically susceptible participants.[19,20,22] While pre-existing disease, the likelihood of undiagnosed cardiac pathology, body mass, smoking history, and baseline fitness all form part of this balance, from the current results it seems advanced age may not necessarily be a critical independent factor in itself, although it is notably associated with greater hypoxemia and with a higher prevalence of comorbidities.

Responses differed between the three suborbital profiles investigated in this study. The vertical rocket-launched capsule profile, which involves the least exposure to $+G_z$, was less provocative physiologically although nevertheless stimulated the processes that were evident to a greater extent during spaceplane profiles. As well as fare-paying participants, our findings have some relevance for suborbital flight crew who experience launch and re-entry phases in an upright seated position during piloted spaceplane operations. Suborbital crew are carefully selected, highly experienced and professionally trained, but the passing of a Class 1 or Class 2 regulatory medical does not guarantee the absence of occult disease, and elite pilots can still be dangerously affected by high G.[18] It is therefore prudent to acknowledge the theoretical potential for intrusive effects in crew that, at the extreme, could cause in-flight incapacitation.

Detailed and continuous physiological measurements during high-G acceleration are challenging to conduct and rarely reported. The comprehensive, synchronous dataset is a strength of this study which, to our knowledge, is the first to present such data relating to suborbital high-G acceleration. The targeted recruitment process achieved a balance of male and female subjects across the desired age ranges, and also resulted in a high prevalence of prior $+G_z$ experience. Although it could be speculated that generic $+G_z$ experience protected the subjects in some way, such that even greater effects might be seen in inexperienced suborbital participants, in reality their experience is unlikely to have had any substantive effects on our findings. Standard technical limitations of acceleration research applied to this work, including the potential for changing hydrostatic gradients to confound blood pressure measurements, although this was minimized by carefully securing the hand at heart level. Noninvasive cardiac output techniques are subject to inherent limitations but are used widely in clinical practice and research, including on centrifuges.[16,21] The acceleration profiles and seating orientation used in the protocol closely approximated, but were not identical to, those used in current suborbital operations, in accordance with the aim of generating boundary data relevant to both current and future platforms. It remains possible that more subtle physiological effects may have been detected with a larger sample size.

The data reported here were obtained in healthy individuals across a wide age range, providing an important foundation that allows extrapolation to other individuals and populations. Ultimately, further research will be required to explore the equivalent responses in populations with diverse pathophysiology. Studies should investigate whether anticipatory 'pre-tensing' of the leg muscles can prevent visual symptoms (and thus also the risk of G-LOC) during suborbital G profiles, and evaluate the role of preflight centrifuge familiarization and judicious assessment using a G challenge test.

In conclusion, this study demonstrates that centrifuge-simulated suborbital G profiles generate highly dynamic cardiovascular responses and pronounced respiratory effects. Transient respiratory symptoms are common and G-induced hypoxemia can occasionally become substantial under air-breathing conditions, and more so under simulated airline-style cabin pressurization. Increasing age accentuated this hypoxemia but did not have detrimental cardiovascular effects, and overall our results are generally reassuring with respect to possible adverse effects of advanced chronological age per se. All effects were greater with spaceplane profiles, which caused frequent visual G symptoms and one episode of G-LOC, emphasizing that suborbital acceleration profiles are not physiologically inconsequential. The effects reported here are unlikely to trouble most suborbital participants but may impact on a minority who are medically susceptible. The continuing development of an evidence-based medical approach would benefit from further research investigating the potential role of preflight centrifuge-based familiarization and assessment, with the goal of enabling safe suborbital spaceflight for as many people as possible.

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Keratoconus and Fitness to Fly

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BACKGROUND: Of the body senses, vision is the most important for safe flight. Keratoconus causes progressive blurring and distortion of vision, which threatens the career of a civilian or military aviator. The goal of this retrospective study was to describe a series of keratoconus cases in a pilot population and to discuss decisions about their flight waivers.

METHODS: To assess the impact of keratoconus on flying careers, we reviewed the records of all aviators with keratoconus examined in an Aeromedical Center over the past 5 yr.

RESULTS: The files of 19 pilots [13 line pilots and 6 military pilots (3 fighter pilots)] were collected and analyzed. Of the 19 patients, 2 did not obtain flight fitness waivers. Among the 17 who received waivers, correction for defective distant vision (glasses or contact lenses) was imposed on 5 aviators.

DISCUSSION: Keratoconus is a medical condition with aeromedical significance that should be detected by aeromedical examiners. A flight license can only be considered if the disease is stable and with satisfactory visual quality. Double pass aberrometry may be helpful to determine flight fitness. This study shows that keratoconus is not always a disability for aviators. Most of them are able to continue their flying careers safely. However, it must be analyzed on a case-by-case basis.

KEYWORDS: expertise, flight fitness, pilots, keratoconus, vision, visual quality.

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Keratoconus is an ectatic corneal dystrophy characterized by noninflammatory, apical thinning and conical protrusion of the cornea. This condition usually manifests itself as a bilateral irregular astigmatism. The disease occurs in all races, bilaterally and asymmetrically. The prevalence of keratoconus in the whole population is 1.38 per 1000 population.[9] Keratoconus typically commences at puberty and progresses to the mid-30s, at which time progression slows and often stops. Between age 12 and 35 it can arrest or progress at any time and there is no way to predict how fast it will progress or if it will progress at all.[6] In general, young patients with advanced disease are more likely to progress to the point where they may ultimately require some form of surgical intervention. The disease stabilizes more after the fourth decade. Symptoms are highly variable and, in part, depend on the stage of progression of the disorder. Keratoconus may result in blurred vision, light sensitivity, nearsightedness, and double vision, leading to profound visual loss.

There are many keratoconus treatments options available today.[1,15] Treatment for keratoconus depends on the severity of the condition and how quickly the condition is progressing. Generally, there are two approaches to treating keratoconus: slowing the progression of the disease and improving vision. If keratoconus is progressing, corneal collagen cross-linking might be indicated to slow or stop the progression.[22] This procedure strengthens and stabilizes the cornea by creating new links between collagen fibers within the cornea. Corneal collagen cross-linking is effective at stabilizing corneal topography and visual acuity over the long term in patients with progressive keratoconus.[14] A small percentage of treated eyes may continue to progress.[20,21] However, this treatment does not reverse keratoconus.[18–20] Improving vision depends on the severity of the disease. Mild to moderate keratoconus can be treated with eyeglasses or rigid gas permeable contact lenses.[10] This will likely be a long-term treatment, especially if the cornea becomes stable with time or from cross-linking.

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Intrastromal corneal ring segments are medical devices made of synthetic material designed to alter the morphology and refractive power of the cornea. Intrastromal corneal ring segment implantation is a safe and reversible technique that can achieve corneal flattening and improved visual outcomes.[3,11] In some people with keratoconus, the cornea becomes scarred with advanced disease or wearing contact lenses becomes difficult. In these people, cornea transplant surgery might be necessary.

Vision is probably the most important of the aviator's senses. Any decrease in visual acuity potentially poses a threat to flight safety. When a member of the aircrew is referred for keratoconus, flight fitness becomes questionable.

The development of new therapies and vision quality assessment devices currently allows assessing the fitness of an applicant with some flexibility in standards in some cases. In civilian aviation, applicants with keratoconus may be assessed as fit if visual requirements (hypermetropia not exceeding +5.0 diopters; myopia not exceeding −6.0 diopters; astigmatism not exceeding 2.0 diopters; anisometropia not exceeding 2.0 diopters) are met with the use of corrective lenses. Civilian pilots must meet refractive criteria and distance visual acuity, with or without correction, which must be at least 6/9 (0.7) for each eye separately, and at least 6/6 (1.0) with both eyes. Medical reports of the applicants shall be referred to the medical assessor of the licensing authority if the visual requirements are not met. The licensing authority can decide if a derogation from the medical standards can be obtained if the pilot does not meet the visual requirements (eye refraction or visual acuity).

At the initial examination, in French military aviation, the pathology is an absolute disabling condition. Even forme fruste keratoconus leads to an unfit to fly decision due to the risk of progression of the disease. No military pilot can start training if he has keratoconus. In revalidation and renewal examinations, in the case of keratoconus, the military pilot shall be referred to the defense aeronautics medical commission to obtain a derogation to fly. This commission decides on fitness to fly according to the medical files on a case-by-case basis.

In French (civilian and military) aviation, nearly 16,000 examinations are conducted on aircrew members (4000 pilots) in the Ophthalmology Department of the National Pilot Expertise Center (Clamart, France) each year. The mission of this center is to select and monitor aircrews. It is the main center for military personnel and supports many private pilots and those employed by commercial airlines.

When keratoconus is identified during a routine visit, the information is recorded in a register, allowing us to locate the records of these patients for analysis. A corneal topography is performed systematically during the first visit for all pilots and at the request of the ophthalmologist if it is necessary during a routine visit. If the visual requirements are met, a periodic evaluation is performed by an ophthalmologist.

The objective of this retrospective study is to describe a case series of keratoconus in an aircrew population and to discuss decisions about their flight fitness.

METHODS

Subjects enrolled in this study were flying aviators who demonstrated evidence of keratoconus on corneal imaging. Exclusion criteria were patients with low quality topographic maps that did not meet the minimal quality required by the system. The study was approved by the Ethics Committee of the Percy Army Training Hospital.

Our study focused on patients with expertise records examined between 2016 and 2021. It involved all aviators who presented with keratoconus responsible for unfitness to fly during systematic monitoring at the Ophthalmology Department of the National Pilot Expertise Center. Medical records were retrospectively examined, and the following data were analyzed:

- Age, gender, aeronautic specialty;
- Date of diagnosis, time of follow-up;
- Visual acuity (best corrected and uncorrected distance and near visual acuity);
- Corneal topography parameters (central corneal thickness, thinnest point pachymetry, flat k value, steep k value, mean k value, maximum keratometry) measured with a Scheimpflug camera (Oculus Pentacam Rotating Scheimpflug Camera; Oculus, Wetzlar, Germany);
- Objective scatter index (OSI) with HD Analyzer© (Visiometrics, Cerdanyola del Vallès, Espagne);
- Modulation transfer function cutoff frequency (MTF cutoff) with the HD Analyzer©. The intersection between the MTF curve and the abscissa axis corresponds to the cutoff frequency.[8] It is normally given that a cutoff frequency of 30 cpd in contrast sensitivity function corresponds to a visual acuity of 20/20;
- Pearson correlation coefficient was used to measure the strength of a linear association between MTF cutoff and best corrected distance visual acuity;
- Keratoconus stage classified into four stages according to the Amsler-Krumeich classification;[12] and
- Fitness-to-fly results.

RESULTS

The files of 19 pilots [13 line pilots and 6 military pilots (3 fighter pilots)] were collected and analyzed. The military pilots with keratoconus did not suffer from keratoconus on their initial examination. All these pilots began their pilot training with normal corneas. Keratoconus developed during their careers, unlike the civilian pilots, some of whom already had keratoconus.

All the pilots were men. Each patient presented with bilateral involvement. The candidates were on average 22.42 ± 2.03 yr of age at the time of diagnosis (**Table I**).

Eight pilots were declared fit to fly without limitation. Nine pilots were declared fit to fly with optical correction limitation (valid only with correction for defective distant vision or correction by means of contact lenses). Two were declared unfit to fly.

Table I. Summary Table.

PILOT	BIRTH YEAR	JOB	AGE AT THE TIME OF DIAGNOSIS (yr)	CURRENT AGE (yr)	KERATOCONUS STAGE (INITIAL EXAM)	CURRENT KERATOCONUS STAGE	CURRENT BCVA (DECIMAL)	CURRENT CCT (μm)	CURRENT KERATOMETRY GREATER CURVATURE (D)	CURRENT MEAN KERATOMETRY	CURRENT ASTIGMATISM (D)	CURRENT OSI	CURRENT MTF CUTOFF (cpd)	FLIGHT APTITUDE	OPTICAL CORRECTION LIMITATION
1	1981	MP (FP)	25	40	0	1	1.0	482	47.7	44.7	1	0.6	36.5	Derogation	VDL
					0	2	0.9	495	47	45.6	1.75	1	34.7		
2	1979	MP (FP)	24	42	0	1	1.0	494	46.9	45.7	2	1.6	16.9	Derogation	None
					0	1	1.0	488	48.6	44.6	0.75	1.2	21.7		
3	1984	MP	22	37	0	2	0.8	485	47.2	45.8	1.75	1.9	21.7	Derogation	VDL
					0	1	1.0	478	46.8	45.4	1.25	1.8	23.8		
4	1992	MP	24	29	0	1	0.9	548	48.2	44.8	1.5	0.8	34.9	Derogation	None
					0	1	1.0	527	47.5	43.9	0.75	0.7	31.9		
5	1990	MP	22	31	0	2	0.8	482	49.7	43.7	2.25	1	32.2	Derogation	CCL
					0	2	0.8	507	50.6	44.4	1.75	1.4	23.8		
6	1996	MP	23	25	0	2	0.6	479	51.2	47.4	2.00	1.8	8.2	Unfit to fly	
					0	2	0.7	472	52	47	2.5	2	5.3		
7	1991	LP	25	30	0	2	0.7	499	49.8	47.9	2.75	2.6	11.7	Derogation	VDL
					0	2	0.7	485	51.6	47.3	2.25	2.8	12.8		
8	1997	LP	20	24	1	1	0.8	517	46.9	45.3	2.75	3.1	7.9	Derogation	VDL
					1	1	0.9	531	46.5	45.7	3.5	2.6	16.5		
9	1983	LP	21	38	1	1	1.0	505	48	43.3	2.25	2.2	21.6	Fit to fly	VDL
					1	1	0.9	510	49	43.9	2.75	2	24.8		
10	1985	LP	23	36	0	1	1.0	548	45.4	45.6	2.25	1.5	15.7	Fit to fly	None
					0	1	1.0	487	46.4	45.7	2.5	0.9	36.2		
11	1995	LP	19	26	1	3	0.6	513	52.8	49.6	2.75	3	10.8	Derogation	CCL
					1	2	0.7	532	50.6	48.7	3.5	2.4	12.8		
12	1986	LP	25	35	0	1	1.0	420	47.3	45.5	2.5	1.9	15.8	Fit to fly	None
					0	1	1.0	449	47.5	44.6	2	0.9	26.9		
13	1983	LP	21	38	2	3	0.6	451	52.2	48.6	2.75	3.6	6.3	Derogation	VDL
					2	2	0.8	487	51.7	48.9	3.5	3.4	4.9		
14	1995	LP	21	26	1	1	0.8	485	47.3	44.2	1.75	1.6	24.8	Derogation	VDL
					1	1	0.9	488	48	45.3	2	1.3	22.9		
15	1992	LP	25	29	0	2	1.0	448	50.8	46.7	2.75	2.3	9.7	Derogation	VDL
					0	3	0.6	536	51.1	47.2	2.5	2.9	15.5		
16	1991	LP	24	30	0	1	1.0	531	46.8	43.5	1.25	0.8	35.8	Fit to fly	VDL
					0	1	1.0	410	47.9	44.6	2	1.4	17.7		
17	1980	LP	23	41	0	1	1.0	503	47.8	45.2	1.5	0.8	23.9	Fit to fly	None
					0	1	1.0	520	49.1	44.9	1.75	1.1	22.6		
18	1990	LP	20	31	1	2	0.9	510	50.8	47.8	2.25	3.1	13.6	Fit to fly	VDL
					1	2	1.0	503	50.1	47.6	1.75	3.3	9.4		
19	1994	LP	19	27	1	3	0.6	481	52.9	48.1	2.5	3.8	7.5	Unfit to fly	
					1	3	0.5	476	53.5	49.1	2.75	4.2	6.2		

BCVA: best corrected visual acuity; CCT: central corneal thickness; OSI: objective scatter index; MTF: modulation transfer function; MP: military pilot; FP: fighter pilot; LP: line pilot; VDL: valid only with correction for defective distance vision.

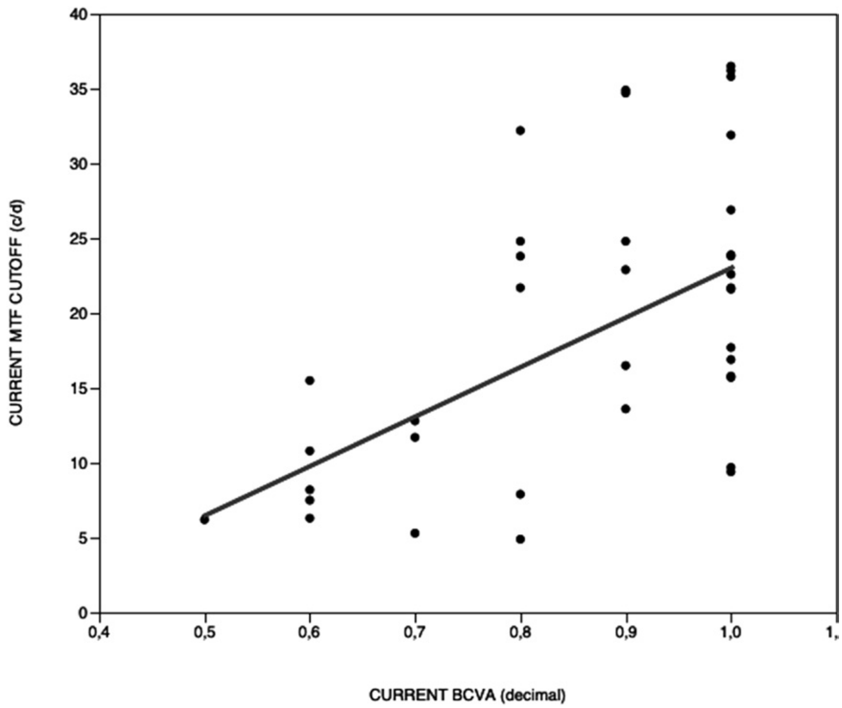

Fig. 1. Relationship between best corrected visual acuity (BCVA) and modulation transfer function cutoff frequency (MTF cutoff).

Six military pilots (three fighter pilots) with ages between 24 and 42 yr (mean age: 32.4 ± 5.7) presented with stage 1 keratoconus (N = 6 eyes) or stage 2 keratoconus (N = 6 eyes). The anterior and posterior corneal elevation maps were considered normal at the initial exam (not suspicious of keratoconus). All these pilots met the requirements for admission to pilot training during their first medical examination.

Using decimal notation, current best corrected visual acuity (BCVA) for all these military subjects was equal or better than 0.6. The average maximum keratometry was 48.6 ± 1.8 D, with a range of 46.8 to 52.0. Visual quality assessment was performed using a double pass aberrometry for each pilot; the mean OSI was 1.49 ± 0.80 and the MTF was 24.3 ± 10.3.

Five of these pilots were declared fit to fly after derogation by the French Military Authority, and two of them needed to wear correction for defective distant vision and carry a spare set of spectacles. One of them needed correction by means of rigid gas permeable contact lenses. Only one was not fit to fly.

There were 13 civil pilots with ages between 24 and 41 yr (mean age: 31.6 ± 5.3) who presented with keratoconus in different stages (Stage 1, N = 14 eyes; Stage 2, N = 7 eyes; Stage 3, N = 5 eyes). Seven of these pilots began their career with keratoconus; the corneal dystrophy was diagnosed during the selection visit.

Using decimal notation, BCVA was measured; all had equal or better than 0.5. The mean maximum keratometry was 49.3 +/2.3 D, with a range of 45.4 to 53.5 D. Among these cases, three pilots had undergone cross-linking therapy treatment. In this group, the mean OSI was 2.1 ± 0.85 and the mean MTF was 16.7 ± 8.6.

Six of these pilots have received an aviation medical certificate from the French Civil Aviation Authority. Correction for defective distant vision and a requirement to carry a spare set of spectacles (glasses) was imposed on eight aviators. One of them needed correction by means of rigid gas permeable contact lenses, another one was unfit to fly.

We found a significant positive correlation between MTF cutoff frequency and BCVA [Pearson correlation coefficient (ρ) = 0.5663 95%CI (0.3011, 0.7502)] (**Fig. 1**).

DISCUSSION

This study analyzed the career impact of keratoconus in aviation. We found that 17 of 19 aviators (89%) retained sufficiently corrected vision to remain able to fly at their last examination.

If pilots do not meet fitness standards, a civilian or military medical board may issue a flight waiver. These commissions rule according to a set of criteria ranging from the age of the pilot, the type of aircraft, the visual acuity, the stage of keratoconus, the evolution of the disease, and the vision quality.

The population of this study only includes men, which can be explained by the characteristics of the population studied. The percentage of female fighter and transport pilots in the French army is 2.3%[16] and approximately 10% in civilian aviation.

Due to careful initial medical selection, the number of pilots suffering from keratoconus is rare. The diagnosis of keratoconus is now facilitated by efficient topographers, which allows analysis of anterior and posterior corneal elevation. This probably explains why no military pilot has recently developed a keratoconus during their career.

With the development of computer processing, some new quantitative evaluation technology of vision quality is available.

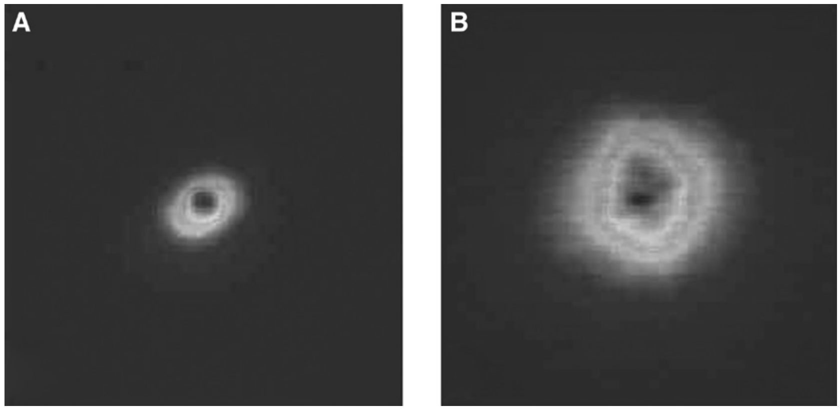

Fig. 2. Two-dimensional point-spread function plots derived from double-pass retinal imaging (HD Analyzer©). A) subject without keratoconus; B) subject with keratoconus.

The optical quality analysis system (HD-Analyzer©) is a double-pass system that is a convenient and objective method for visual quality assessment, including the higher order aberrations and scattered light. OSI provides information on the relevant forward scatter that affects vision.[2] This index may represent a clinically significant parameter that can evaluate quality of vision. OSI for normal eyes would range around 1, while values greater than 5 would represent highly scattered systems. Leonard et al. indicate that OSI may be useful in the diagnosis and staging of keratoconus given the significant increases observed at mild and moderate severity of keratoconus.[13] They did not show any significant differences between the OSI values of normal subjects and those with mildly atypical topography [early keratoconus (Stage 1) and moderate keratoconus (Stage 2)], suggesting that the quality of the retinal image in these patients is relatively normal. These results are similar in our study. We included moderate forms of the disease, which is probably why OSI values are low. On the contrary, Ren et al. reported that vision quality in the forme fruste, mild, or moderate keratoconus was inferior to that in normal vision.[19] The HD-Analyzer© gives important qualitative information, helping practitioners better understand the visual circumstances that pilots with keratoconus suffer from, particularly with more advanced forms of the disease.

The point spread function provides information on the overall optical performance of the human eye: it is the irradiance distribution of light from a point source projected onto the retina and it indicates the extent of blurring of the retinal image. This image is useful to easily evaluate vision quality (**Fig. 2**).

We found a significant positive correlation between MTF cutoff frequency and BCVA. The blurring of the retinal image reduces the subjective visual acuity, which is directly related to the MTF cutoff value, although it is not affected by retinal and neural factors. It is normally assumed that a cutoff frequency of 30 cpd in contrast sensitivity function corresponds to a visual acuity of 20/20.[17]

Most patients with keratoconus are managed with glasses or contact lenses for visual rehabilitation. However, although visual acuity may be improved, other aspects of visual function, such as contrast sensitivity or glare, may still be affected.[4] The residual aberrations significantly reduced contrast sensitivities at low and intermediate spatial frequencies for keratoconic eyes wearing rigid gas-permeable lenses.[23] Soft contacts have been proven to provide an operational advantage over the wear of spectacles in missions that require maneuvering flight, the use of night vision goggles, the wear of an oxygen mask, and the ability to quickly look to the far limits of lateral gaze, but some lenses have a high risk of inducing corneal hypoxia in flight due to poor oxygen transmissibility.

Contact lenses remain stable under load factors; Flynn et al. did not notice significant decentration of the contact lens during a test in a human centrifuge.[7] Dislodgement of a hard contact lens with acceleration, loss of the contact lens from the eye, and bubbles forming under the contact lenses during rapid decompression are possible. Hard contact lenses are even less stable on keratoconic eyes due to the abnormal shape. Dennis et al. showed a descent down the z-axis of 2–3 mm during a centrifuge test.[5] This type of contact lens seems not suitable for fighter pilots.

Military fighter pilots require perfect vision due to the nature of combat military aviation. The selection of these pilots is rigorous, so the detection of a keratoconus is a concern of ophthalmologists working at the National Pilot Expertise Center. The development of a keratoconus during a career would remove the fighter pilot from flight status. It is necessary to refer military pilots with keratoconus to the defense aeronautics medical commission. In some cases, derogations from medical standards can be obtained in order to fly again. The situation for airline pilots is different; keratoconus can be tolerated if the quality of vision does not deteriorate.

In conclusion, keratoconus is a medical condition of aeromedical importance and should be reported to aviation medical examiners upon diagnosis. At the initial examination in military aviation, the pathology is an absolute disabling condition. Certification in civil aviation is possible in cases where there is stable disease with a stable response to vision correction and correct visual quality. As the disease can potentially progress over a short period of time, the validity of medical aeronautical certification may be shortened accordingly (from 6 mo to 1 yr), especially in affected younger applicants, whose disease could advance more aggressively. Glare, distracting distortions, and monocular diplopia are symptoms that deserve special attention and make keratoconus a cause of incapacitation during flight. HD-Analyzer© images contain information about the vision quality of the eye. This device could be useful to decide whether or not the applicant is fit to fly in the case of keratoconus as it is not always a disability for aviators. Most of these pilots are able to continue their flying careers safely. However, it must be analyzed on a case-by-case basis.

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A Digital Alternative to the TNO Stereo Test to Qualify Military Aircrew

Bonnie N. Posselt; Eric Seemiller; Marc Winterbottom; Chris Baber; Steve Hadley

INTRODUCTION: Stereopsis is usually required in military aviators and may become increasingly important with reliance on newer technologies such as binocular Helmet-Mounted Displays (HMDs) and stereo displays. The current stereo test used to qualify UK military aircrew (TNO test) has many limitations. To address these limitations, two computer-based digital versions of a random dot stereogram (RDS) were developed: a static version (dRDS-S), and a version in which the dots appear to move dynamically within the depth plane (dRDS-D), both capable of measuring stereo acuity to threshold.

METHODS: There were 41 participants who performed all 3 stereo tests, TNO and both digital dRDS tests, on two separate occasions.

RESULTS: The best (lowest) mean stereo acuity threshold was measured with dRDS-S (33.79 arcseconds, range 12.64–173) and the worst mean stereo acuity thresholds were measured with the TNO test (91 arcseconds, range 60–240). Both dRDS tests were strongly correlated, but neither correlated with the TNO test. Both dRDS tests were more reliable, as indicated with tighter limits of agreement.

DISCUSSION: With a large floor effect at 60 arcseconds, the TNO test was unable to characterize any finer degree of stereo acuity. Both dRDS tests demonstrated better test-retest reliability and addressed many of the limitations seen with the TNO test. The dRDS tests were not correlated with the TNO test, which suggests that the TNO test does not provide the accuracy or reliability for use as a meaningful aeromedical screening test. The dRDS tests will enable research to investigate the relationship between stereo acuity and operational performance.

KEYWORDS: stereo acuity, stereo test, vision standards, aviators.

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Since the dawn of powered flight, adequate vision has been considered vital in aviators, and numerous vision standards exist to qualify aircrew to fly. However, some vision tests used by aeromedical examiners today could be considered outdated and crude, with many limitations. There is a need to evaluate vision tests used for military aviators to assess whether they are fit for the purpose or if newer test methods could be more effective and appropriate.[24]

Stereopsis, in particular, is desired in military aviators for its link with binocular vision and depth perception, which, in turn, are thought to benefit flying performance.[31,43] As stereopsis is largely exercised for closer visual ranges, but up to 18 m,[2] adequate stereo acuity is most advantageous in situations operating in close proximity to other aircraft such as air-to-air refueling, taxiing, and formation flying. However, stereopsis may become increasingly important with the advent of newer visually demanding technologies such as binocular Helmet Mounted Displays (HMDs) and stereo displays.[24] In essence, stereopsis is the ability to perceive precise depth based on the difference in position of an image between the left and right retinas due to the slightly different perspective of each eye (binocular disparity). Stereo acuity is the smallest disparity that can be perceived in depth and is one way to measure binocular function. Stereo acuity varies significantly among individuals and in the general population ranges from a few arcseconds to more than

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hundreds of arcseconds,[11] with a proportion of people (5–30%) lacking stereopsis altogether.[4,27] For those with measurable stereo acuity, there is a bimodal peak in the general population at 96 and 699 arcseconds[11] which does not appear to be affected by age according to some studies,[11] but found to deteriorate over 50 yr of age in others.[12] A further 32% of people are stereo anomalous despite otherwise normal vision.[11]

As demonstrated by the significant proportion of people with deficient stereo acuity, stereopsis is not essential to daily life. One can rely solely on monocular cues, also known as pictorial or object-centered cues, to perceive depth. Such monocular cues are: relative size, interposition, linear perspective, aerial perspective, textural gradient, atmospheric shading, luminance, height in visual field, and motion parallax.[39] It is also possible to successfully pilot an aircraft without stereopsis, as evidenced by a few monocular pilots, and monocular vision is allowed in trained civilian pilots of all classes following a 6-mo adaptation period.[34] Despite this, it is generally thought that while not absolutely necessary, stereopsis complements and enhances flying abilities.[31,43] For example, landings performed monocularly are altered with steeper and higher descents[8] and, in some cases, aviation mishaps have been attributed to a lack of stereopsis.[21]

Across all three UK military services, aircrew must meet the required entry stereo acuity vision standards set out in AP1269A.[29] These standards and test methods are summarized in **Table I** and compared with U.S. military and civilian stereo acuity vision standards. Among the Five Eyes Air Force Interoperability Council (AFIC), all but Australia test their aircrew population for stereo acuity, while Canada tests for stereo acuity but does not enforce any stereopsis standard.

As shown, a number of different stereo tests are employed and not all are necessarily comparable.[16,26,36] The Howard-Dolman, Verhoeff, and Frisby tests use real life depth stimuli. The Titmus, Randot, and Armed Forces Vision Tester (AFVT) use circle contours, all of which by their nature have monocular cues. Random Dot Stereograms (RDS), as the name suggests, are comprised of small random dots whose positions differ between the two eyes and are the only stereo tests to isolate disparity without the use of contours or monocular cues. Because the stimulus can only exist as binocular disparity, RDS tests are often considered the best measure of pure stereopsis.[16]

Tests used to qualify military aircrew, listed in Table I, were all developed for clinical settings and largely for screening purposes. A thorough review of U.S. Air Force stereo test methods is provided by Winterbottom et al.[41] While some of the stereo tests listed use the 'gold standard' RDS method, none of the tests provides a true threshold measure of stereo acuity. Instead, these stereo tests rely only on the ability to detect a disparity with respect to zero and most do not asses the person's ability to differentiate between crossed and uncrossed disparities. Thus, it is eminently possible to score well on one test yet fail another.[14,23] The Operational Based Vision Assessment (OBVA) Laboratory aims to improve test methods to counter the shortfalls in paper-based analog tests, measure vision more reliably, and investigate relationships between vision and operational performance so that decisions regarding vision standards are rooted in evidence. Indeed, newer computer-based tests are continuously being developed and tested both by the OBVA Laboratory and others.[10,16,28] The two digital stereo tests investigated here are digital versions of an RDS (dRDS), which is compared against the Toegepast Natuurwetenschappelijk Onderzoek (TNO) test (**Fig. 1**) used to qualify UK military aircrew.

The TNO test is a seven-page booklet of randomly paired red and green dots which should be viewed at 40 cm using red-green colored glasses. The individual must identify the image and the orientation of the missing segment of the circle, which might be in one of four positions. TNO test stimuli are presented with crossed disparity and thus appear in front of the reference plane. There are two circles for each level of stereo acuity and a subject must identify both correctly to progress to the next level. The binocular disparity of targets is 480, 240, 120, 60, 30, and 15 arcseconds, although the UK military employs a version of the TNO test with only six pages, which means the best score that can be achieved is 60 arcseconds. Unless directly specified, the TNO test referred to in this work is the six-page version used by the UK military. The subjects' scores are then recorded manually by the examiner. The TNO test uses RDS stimuli, so monocular cues should not play a part in interpreting the orientation of the missing segment of circle. As an RDS test, with minimal monocular cues, it is not unexpected that subjects have higher (worse) thresholds on the TNO test compared to a stereo test which is contour based.[9] However, even taking this

Table I. Stereopsis Vision Standards Across UK and U.S. Militaries, as Well as Civilian Organizations.

	UNITED KINGDOM		U.S. AIR FORCE		U.S. NAVY	U.S. ARMY	FAA	CAA
	PILOT	WSO	FC I/II	FC III	CLASS I, II (EXCEPT FIXED WING), CLASS III (INCL. UAV OPERATORS & CRITICAL FLIGHT DECK PERSONNEL)	PILOT CLASS 1 (COMMERCIAL) AND 2 (PRIVATE)	CLASS 1/2/3/4	
Stereo acuity (arcseconds)	120	N/A	40 waivable to 120 on AO-V	N/A	25 (VTA-ND) or 40 (Randot/Titmus/AFVT) or 8/8 Verhoeff; no waiver	Normal binocular vision	40	No standard
Test method	TNO		AFVT	N/A	As above	AFVT; Randot; Titmus	None specified	

FAA = Federal Aviation Authority, CAA = Civil Aviation Authority (UK), AFVT = Armed Forces Vision Test, AO-V = AO-Vectograph, VTA-DP = Vision Test Apparatus-Near and Distant, WSO = Weapon System Operator, FC = Flying Class.[35]

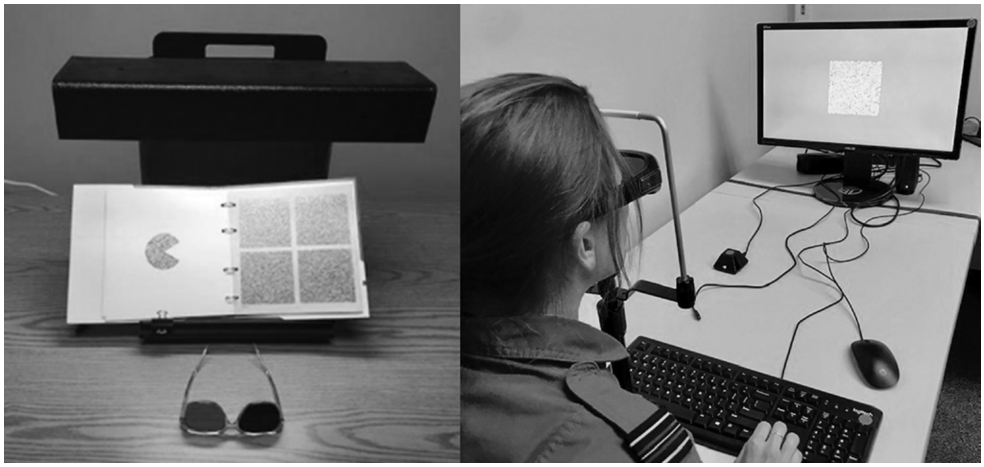

Fig. 1. Left: TNO test booklet with anaglyph glasses on an inclined stand. Right: Set up for dRDS-S and dRDS-D tests. Photograph taken by OBVA personnel.

difference into consideration, performance on the TNO test can be up to 25% worse than with any other stereo test.[20,37] A possible reason why the TNO test results in higher stereo thresholds than even other RDS tests could be that the different color filters in the glasses cause an imbalance in luminance transmittance and contrast.[37] This could be exacerbated further if lighting conditions are suboptimal. Another reason why stereo acuity thresholds are higher using the TNO test is that it is a more complex two-stage process; the user must first identify the circular shape and then indicate the orientation of the missing segment.[9] In comparison, simple detection tests such as the Randot test merely requires the sole stimuli in depth to be identified as the 'odd one out'.[37]

In addition to the TNO test yielding higher stereo acuity thresholds, there are other concerns with using the TNO test to assess stereo acuity. The TNO test has poor test-retest reliability, answers can be easily memorized, and there can be an unacceptable degree of variation between different test editions due to flaws in the printing process.[3] Van Doorn et al. demonstrated a statistically significant difference in stereo acuity results obtained using two separate editions of the seven-page TNO test, with mean measured stereo acuities of 30 arcseconds using one edition and 60 arcseconds using a different edition ($P < 0.001$). These differences were likely due to inconsistent image quality resulting from differences in the printing process.[5] Such profound limitations could result in human-machine technology mismatch with equipment such as stereo displays, which require users to have a minimum level of stereo acuity in order to be perceived and interpreted correctly. Furthermore, crude groups for stereo acuity scores make it impossible to closely track stereo acuity in an individual, as a marker of underlying pathology or effects of clinical treatment, or to monitor recovery to enable a return to flying duties. For example, traumatic brain injury and dementia are associated with worsening stereo acuity,[18,19] and could potentially be detected earlier and appropriately monitored with an accurate and reliable stereo acuity test.

To address some of the limitations of a paper TNO test, two digital RDS tests were developed. This research aims to assess whether computer based RDS tests could offer a fairer, more accurate, more reliable, and repeatable alternative stereo test to qualify military aircrew. Additionally, having the same tests or even comparable tests employed by different countries would improve interoperability with regard to human resources, allowing each country to accept aircrew from allied partner nations without further vision testing. For this experiment, results obtained using three different stereo acuity tests were analyzed.

METHODS

Three stereo tests were used to measure stereo acuity: the TNO test (six-page version) currently used by the UK military to qualify aircrew, and two digital RDS tests: a version in which the dots appear to move dynamically within the depth plane (dRDS-D) and a static version (dRDS-S). All three stereo tests were taken together and repeated a second time on a separate day. Test order was randomized using Microsoft Excel software (Microsoft, Redmond, WA, USA). Participants wore their habitual visual correction for all stereo tests.

Subjects

Recruited from the OBVA subject database were 45 participants. Volunteers were provided with a written information sheet. All participants were required to sign informed consent, indicating permission for their unidentifiable data to be stored and used within the OBVA laboratory. This study was approved by the U.S. Air Force (USAF) Air Force Research Laboratory Institutional Review Board (FWR20170095H).

Equipment

The TNO test is a six-page version with stimuli composed of random dot stereograms viewed at 40 cm using red-green colored glasses (Fig. 1). Reflective luminance of the booklet pages under a broadband reading light (incandescent bulb) was 197 to 306 cd · m^{-2} measured with a handheld Konica Minolta LS-110 (Konica Minolta Sensing America, Ramsey, NJ, USA).

Luminance decreased when viewed through the colored lenses to 13–23 cd · m^{-2} through the red lens and to 3–8 cd · m^{-2} through the green lens. Verbal instructions were given for the TNO test and responses were recorded by the examiner.

Both digital tests use an RDS stimulus similar to the TNO test, a circle with a missing segment, displayed on a 53 × 23-cm 3D computer monitor and viewed through Nvidia 3D active shutter glasses (ASUS, Taiwan) synchronized via an infrared transmitter. The shutter glasses synch with the refresh rate of the screen to ensure that the two disparate images, displayed one after the other, are presented to each eye separately to create a stereoscopic image. The test is performed in a darkened room with the participants' head fixed at 1 m using a chin rest (Fig. 1). The stimulus is presented with crossed disparity, appearing to be forward in depth compared to the plane of the computer screen. The perceived orientation of the missing segment of the circle is entered directly by the subject using the directional arrows on a keypad. The two different versions of the digital RDS test are: 1) dRDS-S and 2) dRDS-D. In the dRDS-S, all dots remain stationary, presented for 8 s. In the dRDS-D, the position of each dot was randomized with each frame refresh to give the dots a dynamic moving appearance (in the x- and y-planes), completely eliminating any monocular cues, also presented for 8 s. The square box measured 14 × 14 cm and the diameter of the stimulus was 7 cm. The mean background luminance of the stimulus was 149 cd · m^{-2} measured with 100% monitor brightness using a Konica Minolta Luminance Meter LS-110. The temporal resolution was 120 Hz (60 Hz to each eye) and spatial resolution 1920 × 1080 pixels. The test was programmed in C# in visualbasic.net using Direct X and a 2.2 gamma correction applied to improve accuracy for subpixel shift. Each dot was defined by a Gaussian function with a sigma of 3.75 pixels and there were 4000 dots randomly placed within the box.

To create the disparate image, three regions were designated within the box: A, B, and C (**Fig. 2**). Region A was the shape of the stimulus at its origin and all dots within it were shifted horizontally to region B and duplicated in region C. The dots in region B are presented only to the right eye and the dots in region C are presented only to the left eye, thereby creating a stereoscopic image. Simply shifting dots from region A to regions B and C creates both gaps between dots and an overlap of dots when regions B and C are viewed binocularly relative to the background dots in the area outside of region A, which could create monocular cues. To correct for this, excess background dots (checked regions) were moved to fill the void areas (striped region) for the opposite eye (Fig. 2).

For both the dRDS tests, instructions were given on the screen. Using the four alternative forced choice method, participants were instructed to choose up/down/right/left orientation of the stimulus. The forced choice model is a more effective way of measuring a detection threshold than relying on signal detection by a subject, which is biased by individual decision criterion.[38] Using four choices is more efficient than using two, reducing the guess rate to 25% with fewer trials needed to reach the detection threshold.[38] Each stimulus was presented for a maximum of 8 s; if no response was given within that time it was logged as an incorrect response. Each participant had a 10-trial practice session using stimuli with disparities of 300 to 2000 arcseconds prior to the formal test to ensure that participants understood the test and to reduce practice effects. Each dRDS test consisted of 45 trials with stereo acuity threshold, standard error, and slope estimate results displayed in an Excel spreadsheet (Microsoft). The Psi paradigm [25] is an adaptive procedure that was used to fit the psychometric function and estimate detection threshold.[13] Disparity of the test stimuli was altered in 0.1 log arcsecond step sizes, based on the participant's previous prior responses (i.e., the test generally got easier if the participant answered incorrectly, but more difficult if the participant responded correctly). The design and thresholding method of the dRDS test enabled each participants' stereo acuity threshold to be measured from 5 to 8000 arcseconds. The lapse rate of the psychometric function was fixed at 2.5%, but the slope was allowed to vary to allow for greater accuracy of the threshold estimate.[25] The lapse rate, which is sometimes called the finger-error rate, accounts for psychophysical errors not directly related to the observer's perception of the stimulus, such as accidentally pressing the wrong response button on the keypad.

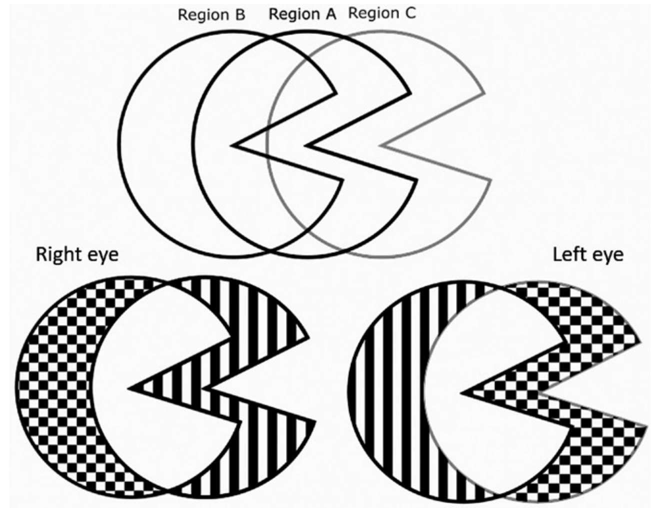

Fig. 2. Top: Region A outlines the original stimulus area. To create the disparate stereo image, the dots in region A are shifted horizontally leftwards to region B, viewed only by the right eye. The dots of region A are shifted an equal distance horizontally rightward to region C, viewed only by the left eye. Bottom: Shifting dots from region A to B, as viewed by the right eye, and to region C, as viewed by the left eye, will result in areas with an excess of dots (checkered area) overlapped onto the background dots, and a void of dots (striped area), creating monocular cues. To correct for this, excess background dots (checkered regions) are moved to fill the void areas (striped regions) in the opposite eye. Image created by OBVA personnel.

RESULTS

Using the OBVA subject database, 45 participants were recruited. One participant did not complete both sessions and

Table II. Mean, Median, Range, and Standard Deviation (SD) of the Three Stereo Acuity Tests.

	dRDS-S	dRDS-D	TNO
Mean – Log arcseconds	1.53 (33.79)	1.78 (59.6)	1.96 (91.56)
Median – Log arcseconds	1.51 (32.63)	1.78 (60.9)	1.78 (60)
Range – Log arcseconds	1.10–2.24 (12.64–173.78)	1.38–2.41 (23.87–197.83)	1.78–2.38 (60–240)
SD (arcseconds)	±0.25	±0.24	±0.22

another participant's data file was corrupted. A further two participants were essentially stereo blind, with scores of 4 and 3.8 log arcseconds as measured with the dRDS-S test. These scores are at the uppermost limit of the tests' capability and are likely unreliable. The final sample size was $N = 41$ (24 men; 37.5 mean age, SD ± 10.1 yr, range 21–70). Analyses were conducted using IBM SPSS Version 26 (IBM Corp., Armonk, NY, USA).

Recruitment was targeted to ensure participants with a wide spread of stereo acuities were included; thus, the sample population is broader than traditional military aircrew populations, who are required to meet the stereo acuity selection standard of 120 arcseconds as measured with the TNO stereo test in the UK and 40 arcseconds as measured by the AFVT for the USAF. Mean and median stereo acuity values are given in **Table II** with a histogram illustrating frequency of results in **Fig. 3**.

Statistical Analysis

A Friedman two-way analysis of variance (ANOVA) by ranks test showed there was a statistically significant difference in the distribution of stereo acuity scores for the three tests [$\chi^2 = 53.12$, df (2), $P < 0.01$]. A post hoc Wilcoxon signed-rank test was performed to determine if there was a median difference between each pair of the different stereo acuity tests. Using a Bonferroni-corrected P-value of 0.012, all test pairs differed significantly (**Table III**).

Bland-Altman plots were used to quantify the reliability of a repeated test, or agreement between two measures, by comparing mean differences and calculating limits of agreement. The closer the mean difference is to zero, the better the agreement between two measures, and the smaller the standard deviation, the more repeatable and reliable a test is. It is considered a better way to understand comparability between two measures than simple correlation analyses, which evaluate only linear association and used on their own could be misleading.[7] It should be noted that while the Bland-Altman method calculates limits of agreement, it is unable to determine whether these are acceptable or not. That is a separate task entirely depending on the user's appetite for risk and need for reliability.

On both attempts of the TNO test, 27 participants achieved the same score (66%), with some participants able to simply remember their answers from the previous session. With Bland-Altman analysis the mean difference between first and second sessions was 0.03 log arcseconds (95% CI = ± 0.05) with limits of agreement ± 0.34 log arcseconds, a combined total of 0.69 log arcseconds (**Fig. 4A**). These limits of agreement are artificially narrowed, since there are only four possible stereo acuity values for the RAF six-page version of the TNO test; thus, a large degree of variance has already been removed. When translated into a real-life example, subjects scoring 120 arcseconds with the TNO may actually have a true stereo acuity varying anywhere between 70.6 to 203.8

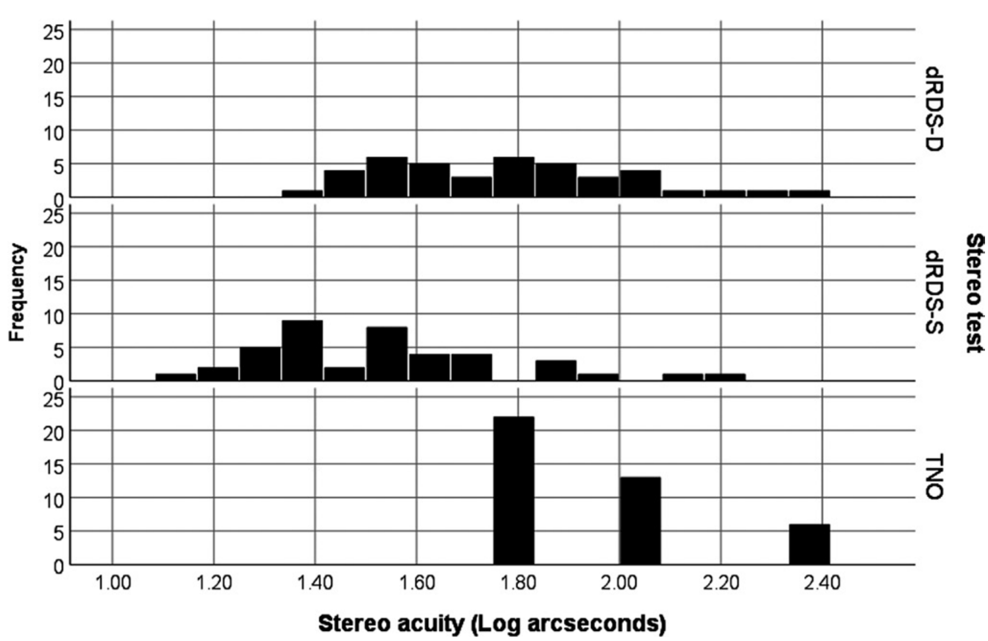

Fig. 3. Histogram of stereo acuity score (log arcseconds) frequencies measured with dRDS-D, dRDS-S, and TNO.

Table III. Wilcoxon Signed Rank Test Between Pairs.

COMPARISON	z-SCORE	SIGNIFICANCE
dRDS-S vs. dRDS-D	−5.18	$P < 0.001$
dRDS-S vs. TNO	−5.40	$P < 0.001$
dRDS-D vs. TNO	−3.58	$P < 0.001$

Significance level: $P < 0.012$.

arcseconds. These results indicate better test-retest reliability than previous reports of a difference of 0.06 log arcseconds and 95% limits of agreement of 1.53 log arcseconds.[32] It is noted that in their test-retest reliability analysis of the TNO test, Tittes et al.[32] used the seven-page version, which incorporated an additional two levels, able to measure stereo acuity down to 15 arcseconds. In our subsequent analyses, the first stereo acuity score was used.

With Bland-Altman analysis the mean difference between first and second dRDS-S sessions was 0.04 log arcseconds (95% CI = ±0.04) with limits of agreement ±0.25 log arcseconds, a combined total of 0.50 log arcseconds (**Fig. 4B**). With Bland-Altman analysis the mean difference between first and second dRDS-D sessions was 0.05 log arcseconds (95% CI = ±0.04) with limits of agreement ±0.23 log arcseconds, a combined total of 0.47 log arcseconds (**Fig. 4C**).

Each stereo test assesses stereopsis using a different method, giving significantly different results. It is important to compare levels of agreement between these tests to aid interpretation and relatability. A simple scatter plot between the two dRDS tests show that they correlate strongly ($r = 0.73$, $P < 0.001$) (**Fig. 4D**). The results of Bland-Altman analysis for stereo acuity scores measured with the two dRDS tests are shown in **Fig. 4G**. The mean difference between them is 0.24 log arcseconds (95% CI = ±0.05), with limits of agreement ±0.35 log arcseconds. There is no significant relationship between the TNO test and either dRDS test (**Fig. 4E** and **Fig. 4F**). With Bland-Altman analysis, the mean difference between the TNO test and dRDS-S is 0.43 log arcseconds (95% CI = ±0.08), with limits of agreement ±0.55 log arcseconds (**Fig. 4H**). With Bland-Altman analysis, the mean difference between the TNO test and dRDS-D is 0.11 log arcseconds (95% CI = ±0.14), with limits of agreement ±0.56 log arcseconds (**Fig. 4I**).

DISCUSSION

With a large floor effect at 60 arcseconds, the six-page paper TNO test was unable to characterize any finer degree of stereo

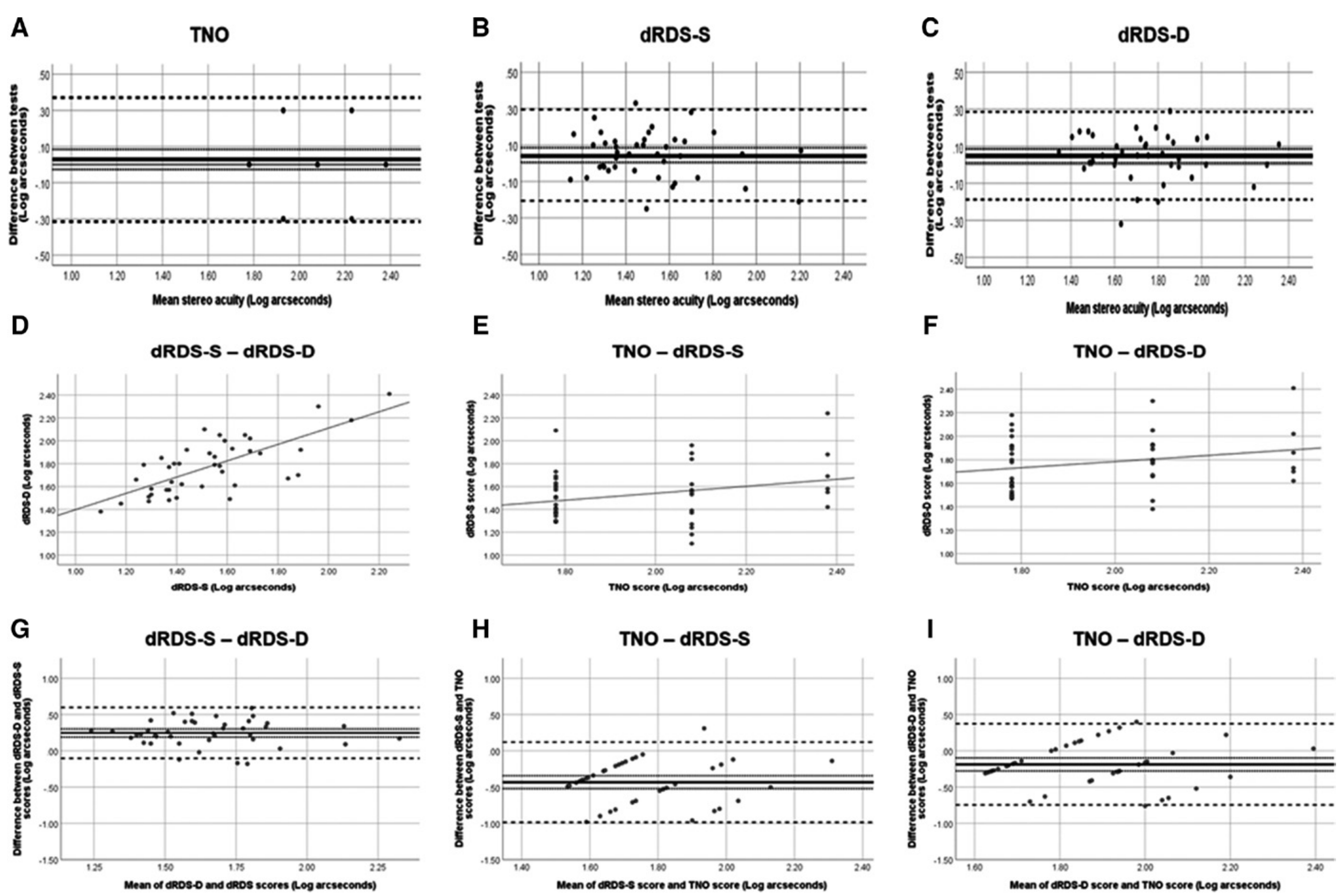

Fig. 4. A-C) Bland-Altman plots assessing agreement between first and second attempts of each test; D-F) correlation analyses between tests; and G-I) Bland-Altman plots of agreement between the three different stereo tests. The thick black line is the mean difference (bias), with the dashed lines indicating the upper and lower limits of agreements. Dotted lines show 95% confidence intervals.

acuity, which, by comparison, was possible using both the dRDS-S and dRDS-D tests. The lowest thresholds (best stereo acuity) were measured using the static version of the RDS (dRDS-S), while the worst scores were reported using the TNO test. Both digital RDS tests were more reliable than the TNO test, as demonstrated with tighter limits of agreement for Bland-Altman analyses. The tightest limits of agreement and, thus, the most reliable stereo test, were seen with the dynamic RDS version (dRDS-D) of the digital tests. With regard to the significant difference in results between the digital tests, a reason why the higher thresholds were recorded using the dynamic version of the dRDS when compared to the static dRDS could be that the dRDS-D is least likely to have any monocular cues and participants found it more difficult. It has been suggested that static and dynamic disparities are processed in a different manner, giving different results when measuring individual stereo acuity,[33,44] and as such these tests may not be directly comparable. However, the dynamic motion applied to the dots in the dRDS-D test is confined to the same plane of presentation and is not a dynamic change in depth. Notably, there was no significant correlation between either of the dRDS tests and the TNO test. An individual scoring 60 arcseconds on the TNO could obtain a score ranging anywhere from approximately 30 to 160 arcseconds on the dRDS-S. This suggests that the TNO test does not reliably measure stereo acuity.

Both computer-based threshold tests eliminated many of the limitations identified with the TNO test. Crucially, the random order of stimulus presentation makes it impossible to cheat or memorize answers, reducing the incidence of false positive results. Furthermore, there is no chromatic imbalance using active shutter glasses, and printing or illumination discrepancies are removed using a standardized computer screen. In addition, examiner interference is minimized, removing the possibility of transcription errors or human bias when giving instructions or recording results. The chief disadvantage of computer-based tests is that they require more expensive hardware resources, in the form of a computer, 3D monitor, and active shutter glasses, to operate. The value of evidence-based medical standards is difficult to quantify. However, given that the estimated cost to fully train a pilot on a 5th generation fast jet aircraft, in which a binocular HMD is critical, is over $10 million,[15] using an operationally relevant stereo test to accurately identify pilot candidates as either medically fit/unfit could significantly reduce the number of pilots unable to complete the intensive training programs, resulting in significant cost savings.

Furthermore, as the computer-based tests are more precise and repeatable, they would be better able to identify more reliably any relationship to operational performance if one exists. Such research is crucial in providing evidence to support aircrew vision standards. Another benefit of more precise vision screening tests is their ability to detect smaller changes in stereo acuity; thus, they are better able to identify medical situations that warrant further investigation at an earlier stage. Currently, no accurate baseline data exist to either better diagnose disease or injury requiring treatment, or to quantify recovery to support return to flying decisions.

There is no clear answer as to which test is the best and most appropriate to use. Such a decision will depend on the tests' ability to predict operational performance and further research is needed in this area. Measuring stereo acuity more accurately could enhance the effectiveness of qualifying standards and our understanding of human performance, as indicated by findings that lower stereo acuity thresholds predict superior performance in an aerial refueling task,[22,40,42] depth related surgical tasks,[1,30] and object placement tasks mediated by stereo displays.[17] Notably, a computer-based stereo acuity test was predictive of simulated air refueling performance in previous research while the AFVT stereo test was not.[42] Further research should also be conducted into stereo acuity measured using frontal dynamic motion-in-depth as this may be a better indicator of overall binocular vision because it includes a time and spatial component.[6]

In addition to these benefits, more reliable threshold estimation tests could support interservice and international co-operation. Currently, the TNO test (UK six-page version) is unable to measure stereo acuity to the vision standards required by the USAF (40 arcseconds). As there are pilots from both the RAF and USAF embedded in each other's flying operations, as part of the enduring exchange programs between allied countries, it is important to have tests that are reliable and clear. We would advocate for aligning aeromedical policy and vision standards to further aid interoperability. Research such as this, aimed at developing vision performance models that predict operational performance, will assist in providing evidence to set vision standards and drive aeromedical policy which can be shared with allied nations.

The limitations of the paper TNO test have been clearly highlighted, with computer-based threshold tests addressing many of these and offering a feasible alternative solution. Digital tests are able to measure individual stereo acuity to a finer degree than the TNO test and do so in a manner that reduces examiner interference or bias and eliminates the possibility of cheating (false positives). For the two versions of the dRDS tests, the static version of the dRDS (dRDS-S) gave the lowest stereo acuity thresholds, but the dynamic version (dRDS-D) was more reliable with the tightest limits of agreement. While the computer-based stereo acuity tests produce significantly different scores, their results are strongly correlated. Neither of the computer-based tests correlates with the TNO test, which suggests that the TNO test does not provide either the accuracy or reliability needed in aeromedical screening for an increasingly digital cockpit environment. The greater granularity achieved with digital tests will enable us to investigate the relationship between stereo acuity and operational performance, which in turn will inform stereo acuity vision selection standards or display requirements. This will be increasingly important for military aviators for whom stereoscopic displays and HMDs are becoming more prevalent and critical to flying operations.

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Cardiovascular Concerns from COVID-19 in Pilots

Wiaam Elkhatib; Dana Herrigel; Michael Harrison; Thomas Flipse; Leigh Speicher

BACKGROUND: Cardiovascular disease, now complicated by the COVID-19 pandemic, remains a leading cause of death and risk for sudden incapacitation for pilots during flight. The capacity for aeromedically significant cardiovascular sequelae with potentially imperceptible clinical symptoms elicits concern both during and following resolution of acute COVID-19 in pilots.

OBJECTIVE: We summarize the current state of knowledge regarding COVID-19 cardiovascular implications as applied to the aviation environment to better understand their significance toward flight safety and application toward a focused cardiovascular screening protocol following recovery from infection.

METHODS: A narrative review of the cardiovascular implications of COVID-19 infection was performed using the PubMed literature search engine and existing organizational guidelines. In addition, to established medical aviation benchmarks, surrogate populations examined included high performance athletes (as a correlate for high G-forces), and scuba divers (as an environmental work analog). Conditions of primary concern included myocardial injury, proarrhythmic substrates, risk of sudden death, myopericarditis, pulse orthostatic lability in response to vigorous activity, cardiovagal dysfunction, and thromboembolic disease.

LITERATURE REVIEW: Cardiovascular screening guideline recommendations post-infection recovery are suggested based on profile stratification: airperson flight class, tactical military, and aerobatic pilots. This provides an approach to inform aeromedical decision making.

CONCLUSION: Aviation medical examiners should remain cognizant of the clinically apparent and occult manifestations of cardiovascular dysfunction associated with COVID-19 infection when applying return-to-work screening guidelines. This will ensure high flight safety standards are maintained and sudden incapacitation risk mitigated during and following the ongoing pandemic.

KEYWORDS: cardiovascular; cardiac; heart; cardiovascular screening; cardiac screening; COVID-19 screening: coronavirus; SARS-CoV-2; Coronavirus disease 2019; aviation; airpersons; airmen.

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Worldwide rigorous aeromedical selection screenings must maintain high standards to minimize significant in-flight incapacitation risk, with particular emphasis on cardiovascular disease.[24] Acceptable medical incapacitation combined risk tolerance causing aircraft incidents approximates 1 per 109 flying hours,[67] maintaining the "1% rule per annum risk threshold" industry standard per the International Civil Aviation Organization.[46] Cardiovascular conditions remain a leading cause of groundings, especially in pilot cohorts older than 50 yr of age,[87] presenting aeromedical examiners medical optimization opportunity to reduce medical incapacitation events in allocating special issuances, and medication suitability screenings as approved by the FAA.[28]

Compressed airline passenger transport schedules intuitively can place physiologic stress on commercial pilots. In addition, the added exposures to high G-forces, hypoxic conditions, thermal stresses, and cognitive strain for high-performance pilots have been shown to potentially present inherent occupational cardiovascular risk factors during and

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after flights despite the absence of other contributing elements due to prolonged sympathetic nervous system activation,[36] vagal withdrawal, cardiac baroreflex sensitivity depreciation,[93] and resulting dynamic heart rate variability reductions.[74] Existing predispositions recently have been exacerbated amid the COVID-19 pandemic, posing dilemmas for the ideal cardiovascular medical care approach to these affected patient populations following infection recovery. The capacity for significant cardiovascular sequelae (i.e., malignant arrhythmias, myocardial infarction, myocarditis, pericarditis, sudden cardiac death) with potentially imperceptible clinical symptoms elicits concern both during and after resolution of acute COVID-19 in pilots. Specific medical risk factor evaluations and clinical management considerations warrant deliberation prior to return to aviation duty. Cardiovascular disease, now complicated by the COVID-19 pandemic, remains a leading cause of death and risk for sudden incapacitation for pilots during flight.

We thus comprehensively summarize the current state of knowledge regarding COVID-19 cardiovascular implications as applied to the aviation environment to better understand its significance for flight safety. Cardiovascular screening guideline recommendations post-infection recovery are suggested based on profile stratification including airperson flight class, tactical military, and aerobatic pilots to provide a suggested approach to inform aeromedical decision making.

METHODS

Literature Review

A qualitative narrative review was performed using the PubMed literature search engine for relevant peer-reviewed articles addressing the implications of mild to severe COVID-19 infection toward heart tissue, circulating cells, and endothelium in high-performance athletes as a correlate for experiencing high G forces, scuba divers as an environmental work analog, occupational and military medicine, and established medical aviation benchmarks toward this target population. Conditions of primary screening concern included hypertension, subclinical myocardial injury as potential proarrhythmic substrate, increased risk of sudden death, myocarditis, pulse and blood pressure lability in response to vigorous activity, cardiovagal and orthostatic dysfunction, and thromboembolic disease. International medical association guidelines, expert consensuses, international societies and government recommendations for athletes, scuba divers, and aircraft pilots were included regarding return-to-work and return-to-play screening guidelines from a cardiovascular perspective via searching the relevant association, organization, or government websites. Given the extensive data pool covering topics overlapping between the cardiovascular system and COVID-19 infection, extracted publication selection was limited to those with greatest perceived relevance to aviation medicine based on the specific topics addressed.

Literature Analysis

A total of 315 sources were retrieved in the English language using the search term groupings [("covid" OR "sars-cov-2" OR "covid-19") AND ("heart" OR "cardiac" OR "cardiovascular")] in combination with boolean operator "AND" plus the following to generate multiple unique searches: (airmen OR pilots OR aircrew OR aeronaut OR aviator), ("players" OR "athletes" OR "professional athletes" OR "sports" OR "athletic"), ("recommendations" OR "return-to-work" OR "return-to-play"), ("scuba" OR "diving" OR "deep-sea" OR "underwater") in further combination with MeSH terms. Further studies were elicited using citation chasing. An end total of 103 sources meeting relevant criteria for inclusion after detailed review were incorporated.

Classification of COVID-19 Severity, Recovery, and Sequelae

Classification of COVID-19 severity was inconsistent across much of the reviewed literature, with a minority of papers not including infectious stratification. However, certain overlapping criteria did emerge which were used as an approximation. For purposes of this paper, COVID-19 infection is generally classified into four categories based on FAA guidelines:[28] asymptomatic or mild (positive PCR with no symptoms or minimal symptoms treated on an outpatient basis without supplemental oxygen needs), moderate (symptoms requiring hospitalization but not admitted to the intensive care unit), severe (symptoms requiring hospitalization and intensive care unit admission), and prolonged outpatient recovery course. Postinfectious recovery according to the Centers for Disease Control and Prevention is defined as 72 h following defervescence without fever-reducing medications, improvement of respiratory symptoms, and at least 7 d following symptom onset. The duration of persistent or "long-haul COVID-19" symptomology varied, though is generally defined by the literature as lasting from 1 wk to 3 mo or greater, serving as a driving motivator for screening guideline development.

FINDINGS

Retrospective studies of hospitalized patients with confirmed COVID-19 infection determined that both pre-existing cardiovascular risk factors and in-hospital cardiac events carried significantly higher mortality,[51] highlighting a relationship between the heart and COVID-19, though most immediate or long-term complications remain primarily respiratory rather than cardiac.[13] Reported COVID-19 infection associated cardiac complications among all degrees of severity include atrial and ventricular arrhythmia, myocardial infarction, nonspecific cardiomyocyte injury as shown by troponin and CK elevations, atherosclerotic plaque instability, intravascular clot formation, myocarditis,[40] development of heart failure,[27] mild pulmonary hypertension, varying degrees of right ventricular dysfunction,[9] reduced left ventricular function, and chronic heart failure exacerbation.[99] While the precise mechanisms of general cardiovascular complications resulting from viral infection remain under investigation, many theories and preliminary study findings have presented possible physiologic pathways.

Mechanisms of Injury in COVID-19

Mechanisms for such dysfunction are thought to be indirectly due to systemic cytokine storm inflammatory upregulation and directly as a result of COVID-19 transmembrane viral entry into perivascular pericytes and cardiomyocytes.[27,40] This has been demonstrated on autopsy report data, even in expired infected patients without cardiac clinical manifestations.[11] In-vitro studies suggest the virus may also cause fusion of cardiomyocytes.[70] While the viral binding target ACE2 is expressed most highly in the heart and lung, its presence in the vascular endothelium, kidneys, and gut mechanistically allow for myocardial, vascular,[27] and multiorgan dysfunction during severe COVID-19 infection.[40,90,102] Viral endothelial inflammation likely contributes to hypercoagulability and hyperfibrinogenemia[43] with resultant microcirculatory dysfunction leading to observed higher rates of myocardial infarction and thromboembolisms, suggesting theoretical benefit to continuing ACE inhibitor and statin use.[45,47,95] Other potential mechanisms may be secondary to immune-mediation, direct cellular injury, coagulation impairment, and treatment side effects.[43,44,85] Not only may the virus directly affect membrane-specific ion channels predisposing to cardiac arrhythmogenesis,[97] but several common antimicrobials therapeutically used such as hydroxychloroquine, macrolides, and fluoroquinolones have potential to induce lethal ventricular rhythm aberrancies secondary to their known QT prolongation on EKG.[81,96] Use of two or more arrhythmogenic agents in symphony with ICU admission carries the highest complication risk.[64] Aircraft pilots remain a population especially susceptible to these underlying mechanistic complications.

Pilots as an At-Risk Population

Coupled with the systemic inflammation and increased sympathetic outflow of COVID-19 infection, pre-existing cardiovascular disease stands as one of the most significant risk factors for adverse cardiac outcomes.[88] Multiple studies and meta-analyses reviewed cite cardiovascular comorbidities such as coronary artery disease, diabetes mellitus, and most frequently hypertension[56] as being common with infected patients.[23,101] They are linked to an over 10 times higher case fatality rate when compared to control groups.[100] Other mortality risk factors include male sex and advanced age,[62] which describes the predominant proportion of certified pilots in the United States of America according to the 2021 FAA Active Civil Airmen Statistics.[29] Young adult pilots are not excluded, with one Indian report citing a high incidence of hypertension in airpersons at nearly 19%.[9] Overall, pilots with pre-existing cardiovascular disease seem to have higher susceptibility to both viral infection and risk of developing more severe complications,[13,82] including arrhythmias.

Arrhythmias in COVID-19

Abnormal cardiac rhythms during infection should be regarded as a major contributing risk factor for adverse flight outcomes like thromboembolisms and hemodynamic compromise, most concerning in high-G aircraft environments. Atrial fibrillation has been cited as the most common arrhythmia,[40] as well as persistent exertional dyspnea, potentially mediated by reduced myocardial perfusion reserve secondary to coronary microvascular dysfunction such as that in hypertrophic cardiomyopathy.[23] Critically ill hospitalized patients have the highest incidence of not only atrial fibrillation,[41,57] but also myocardial infarction[9] and heart failure.[7,91] The highest rates were seen during severe infection requiring ICU admission[9] and conversely the lowest rates in mild-to-moderate cases.[40,91,92] Deep vein and pulmonary thromboses also occur.[43,44] Elevated serum cardiac biomarkers can be detectable during acute infection,[57] including those without known cardiovascular disease history or prior cardiac arrest, and acute myocardial injury has been attributed in up to 12% of hospitalized patients.[103]

The precise incidences and clinical context of these complications remain elusive. Even in generally older adult hospitalized patients with moderate-to-severe infection, a relatively low number of patients (11.6%) was shown to be diagnosed with acute cardiac complications during admission in a large international retrospective study (most commonly atrial fibrillation in ICU patients) and tended to have multiple pre-existing comorbidities including dyslipidemia, hypertension, chronic obstructive pulmonary disease, and chronic kidney disease.[56] Another large international study among hospitalized majority elderly male adult COVID-19 patients, of whom nearly one-third suffered severe infection, found cardiac complications during admission to be at less than 12%, despite a large prevalence of pre-existing comorbid arrhythmias or coronary artery disease.[56] Resulting vascular pathology from COVID-19 ties into elevated stroke risk as well.[18,47] Interestingly, retrospective data regarding hospitalized patients with influenza virus cite nearly the same incidence of cardiovascular associated events (11.7%), though acute heart failure and ischemic disease were those most correlated with influenza infection.[19] Emerging studies on cardiovascular complications in COVID-19 infection, such as that by Lund,[61] cite much lower postinfection risks compared to those previously done, likely due to earlier data having been obtained from individuals with hospital or ICU admission, often lacking control groups, and potentially subject to selection and surveillance bias. Similar data trend uncertainties have been shown in reports concerning myocarditis as well.

Myocarditis in COVID-19

Controversy has centered on myocarditis, pericarditis, and the unknown implications of associated cardiac screening test abnormalities during follow-up examinations of individuals recovered from acute COVID-19 infection. True incidence of asymptomatic myocardial inflammation lingering after COVID-19 resolution is completely unknown,[35] and reports have been published describing sudden cardiac death even in mild, nonhospitalized COVID-19-positive individuals.[53] One example is a small analysis by Puntmann et al. of 100 individuals from the general civilian population who had recovered from severe COVID-19 infection revealing that almost 80% demonstrated some sign of myocardial inflammation on cardiac magnetic resonance (CMR) imaging up to 3 mo postdiagnosis in conjunction with detectable elevations of high-sensitivity troponin independent from other risk factors.[79] A similar study documented findings of myocarditis, pericarditis, pericardial effusions, and intramyocardial enhancement upon imaging, including in patients without pre-existing comorbidities.[99] Several other case reports cumulatively assessed in a review paper have implicated myocarditis as a prominent secondary manifestation of COVID-19 infection.[25] When patient data among a conglomerate review of cases with only mild infection treated on an outpatient basis were isolated in comparison with healthy cohorts, however, few myocarditis cases were found, suggesting potential data over-interpretation in some previous studies.[61,83,84]

It should be noted that CMR imaging studies did not often include healthy control cohorts and that the significance of myocarditis evident by CMR alone in this clinical context remains uncertain, though related cardiac findings have been associated with mortality risk[38] and should not be overlooked. While the more cost-effective 12-lead EKG can also screen for myocarditis, it is not the gold standard for myocarditis rule-out,[96] must be interpreted in the correct clinical scenario, and CMR holds higher negative predictive value.[80] Such considerations become increasingly relevant for the diagnostic approach to airpersons afflicted with persistent cardiac-related symptoms despite otherwise full recovery following acute infection.

Long Haul COVID-19

The term "long-haul COVID-19" was coined to describe syndromic persistent clinical manifestations for weeks to months following acute infection recovery; this condition has been described in between 40–90% of recovered patients and is most pronounced in survivors of severe infection.[47] Published reports also describe persistent orthostatic intolerance and postural orthostatic tachycardia secondary to autonomic imbalance and heart rate variability on ambulatory electrocardiogram (EKG) recordings up to 3 mo into the post-COVID period.[23,37,101] Comparable findings from Mayo Clinic Hospital were shown using standardized autonomic function metrics, though most diagnosed complications were mild.[86] Other common symptoms with potential cardiac implications following acute recovery are fatigue[35,42,47] and chronic dyspnea,[58,61,71] with infrequent reports of residual myocarditis or pulmonary diffusion impairment.[91]

Recommendations based on a literature review by Mitrani for the general civilian population during the convalescent phase (2–6 mo after COVID-19 infection) include obtaining an initial screening EKG, transthoracic echocardiogram (TTE), cardiac monitor depending on residual symptoms upon routine outpatient followup, and cardiologist referral for all afflicted patients with prior history of myocardial injury during the acute infectious phase (i.e., documentation of elevated troponins, B-type natriuretic peptide, or confirmed ST-elevation myocardial infarction).[66] In limited support for these data, the current aeromedical examiner (AME) coronary heart disease diagnosis protocol for open coronary artery revascularization or left main stenting requires a minimum 6-mo recovery period, 3 mo for stenting excluding left main coronary artery or uncomplicated myocardial infarction, cardiologist referral documentation, Bruce protocol cardiac stress testing (type depending on aeromedical class), postevent cardiac catheterization after 3 to 6 mo, depending on cardiac event recovery time, and possible SPECT myocardial perfusion exercise stress test if indicated based on prior stress test results.[1] These considerations for long-term manifestations potentially secondary to viral infection should also include the rare complicating side effects of the vaccinations meant to prevent them.

Vaccination-Related Cardiovascular Concerns in COVID-19

Risks from vaccination against COVID-19 must be balanced against known complications of infection. For example, common transient side effects such as fever combined with dehydration have been shown to potentially lower G-tolerance in high performance aircrafts shortly following injection, most pronounced following the second vaccine dose.[31] Further unfavorable consequences predisposing to orthostasis cited in an online cohort study included nausea, vomiting, diarrhea, dizziness.[5] Small retrospective studies and scattered case reports also describe associated myocarditis following COVID vaccinations without definitive causal relationship,[23] including young healthy males[55] with one severe case requiring intravenous steroids.[73] A recent pooled analysis encompassing 39 studies with mostly young men receiving vaccination concluded positive association of symptomatic but mild myocarditis after initial dosing with generally complete, rapid resolution and an uncomplicated clinical course.[6] Myocarditis following mRNA-based immunization likely remains an overtly exaggerated and infrequent event with approximate incidence of 1 case per 10,000-100,000 vaccinations, typically self-resolving within several days.[8,30]

A summary of clinical recommendations regarding COVID-19 mRNA vaccination by Luk focuses on supportive care in afflicted patients, appropriate specialist referral, and continued recommendation of vaccination for all approved populations.[60] The Advisory Committee on Immunization Practices (ACIP) and Centers for Disease Control and Prevention (CDC) similarly maintain that the benefits of vaccination far supersede any possible risks.[82] The FAA's most recent position entails a 48-h no fly duty interval observation following each vaccine dose.[28]

Sports Medicine Analog Cardiovascular Concerns in COVID-19

Unrecognized COVID-19 sequelae have potential implications for return-to-work considerations in fitness-reliant occupations. Existing cardiovascular-related literature and return-to-play recommendations for high-performance athletes with prior COVID-19 infection was thus reviewed as a comparable correlate to military and high-performance pilots who undergo physiologically stressful aircraft maneuvers, experience hypoxia, and withstand high G-forces while in flight. While the general array of cardiovascular risks following COVID-19 in athletes are likely analogous to the general population, most investigations have found their rates to be lower overall. A systematic review by Hattum analyzed 12 manuscripts comprising 3131 athletes 18-64 yr of age having received CMR or TTE following COVID-19 infection recovery concluded an overall minimal risk ranging anywhere from 0–5% of associated pericardial or myocardial involvement, arrhythmias, and no reports of sudden cardiac death with reported incidences varying depending on study quality.[94] Another comprehensive prospective study of 90 competitive athletes recovered from asymptomatic or mild COVID-19 with median age of 24 yr screened by bloodwork, 12-lead resting EKG, 24-h ambulatory EKG monitoring, TTE, and cardiopulmonary exercise testing found a low but significant cardiac abnormality in 3.3% of subjects.[16] A similar proposed estimate from literature review of isolated case reports approximates incidence under 3%.[21]

Many studies have separately assessed myocarditis manifested in competitive athletes, specifically known to present less overtly in this target population with nonspecific symptoms such as malaise, reduced athletic performance, or elevated heart rate, while currently standing as the third most common cause for sudden cardiac death in athletes under the age of 35.[35] Outcomes have been variable with inconclusive clinical implications. In one analysis, nearly half of the competitive athletes in the study who recovered from mild COVID-19 had CMR imaging findings suggestive of either possible myocarditis or prior myocardial injury.[80] A similar cohort showed imaging signs of resolving pericardial injury without features, suggesting active myocarditis.[21] In contrast, another elite soccer player cohort followed at 2 mo after mild or asymptomatic COVID-19 had no significantly detectable cardiac biomarker abnormalities.[2] A different professional athletic population screened by obtaining serum troponin, resting and stress-test EKG, and transthoracic echocardiogram (TTE) found no abnormalities.[33] Reported cases have largely been clinically silent and their long-term implications uncertain.

Irrespectively, missed diagnoses of silent arrhythmias, myocarditis, orthostasis, or others can pose detrimental risk to both athletes and pilots alike. Several publications and opinion statements from different medical organizations have attempted to establish cardiovascular screening protocols during and after COVID-19 infection for this target population based on the most up-to-date objective data available. Many expert consensus guidelines highlight the potential gravity of post-COVID-19 cardiac sequelae for asymptomatic or mild infection[14,69,78] in support of return-to-play screening measures. Some independent study recommendations suggested a focused medical history and physical with a 10- to 14-d observation period alone following incidental COVID-19 detection in asymptomatic athletes,[32,35,96] and minimum of chest X-ray, EKG, and TTE if they had confirmed or suspected mild infection prior to gradually resuming competitive sports.[41,77,98] However, a study of 571 competitive junior athletes with mild symptomatic or asymptomatic COVID-19 suggested TTE screening is not recommended given exceedingly low incidence of cardiac involvement,[15] with a separate analysis also supporting no additional cardiovascular screening for mild cases.[35] Another large cohort study of 789 professional athletes fully recovered from asymptomatic or mild COVID-19 (majority 25-yr-old men) found no adverse cardiac events following extensive cardiovascular screening and subsequent sport participation resumption, reinforcing the updated American College of Cardiology expert consensus discouraging cardiovascular risk stratification in athletes fully recovered from mild infection.[63] An additional cohort study produced an analogous verdict,[33] as well as an analysis by Phelan et al. when weighing medical resource utilization and health care costs.[78]

The European Society of Cardiology[84] and Canadian Cardiovascular Society[65] recommendations for moderate and severe COVID-19 infection are the same as those for mild cases in absence of persistent cardiovascular symptoms, echoed by the *Hellenic Journal of Cardiology* recommendations regardless of infection severity.[72] Moderate-to-severe infection in competitive athletes, abnormalities in initial cardiac screening modalities, and any ongoing symptoms such as, but not limited to, chest pain, dyspnea, swelling, palpitations, orthostasis, decreased functional performance, and vital sign aberrations, warrant cardiology referral for continued investigations to likely involve cardiopulmonary exercise testing and CMR imaging.[84,89,98]

Any diagnosis of myocarditis in young, physically active adults requires at least 3 mo of complete rest pending resolution of serum biomarkers of myocardial injury, ventricular systolic function normalization, and specialist clearance in addition to previously mentioned recommendations following exercise testing plus 24-h EKG monitoring per the 2020 European Society of Sports Cardiology, American College of Cardiology, and Dutch Sports Cardiology Section of the Netherlands Society of Cardiology recommendations.[49,76,96] The rationale for temporary discontinuation of competitive play following any classification of COVID-19 infection, especially with myocarditis or pericarditis, is based on the potential for greater cardiac damage due to the virulence-promoting effects during vigorous activity.[10,32] No clear consensus yet exists for clinically relevant cut-offs for troponin levels or imaging findings.

Hyperbaric Medicine Analog Cardiovascular Concerns in COVID-19

Competitive sports and military aviation generally require more stringent athleticism compared to scuba diving, though minimum medical fitness levels are recommended due to the physiologic effects of underwater immersion, including increases in cardiac preload, cardiac output, blood pressure, diuresis, oxygen partial pressure, bradyarrythmogenisis secondary to combination breath holds and hypothermic exposure, and potential secondary effects of decompression sickness, which may all aggravate pre-existing cardiovascular disease.[68] Recreational diving requires at least 6 METs and commercial divers 10 METs with additional reserve of 13 METs in case of underwater emergencies.[54] One expert consensus article addressing return-to-work screening recommendations for fully recovered scuba divers,[54] as well as The European

Underwater and Baromedical Society (EUBS) and the European Committee for Hyperbaric Medicine (ECHM),[26] suggest no cardiovascular-related screening for asymptomatic and mild COVID-19 cases, EKG and TTE for moderate cases, and specialist referral for cardiac stress testing with serum troponin/BNP measurement for severe cases, residual cardiac-related symptoms, or screening test abnormalities. The overall approach to cardiovascular screening guidelines after infectious recovery of scuba divers is relatively more concise, albeit largely comparable to existing aviation authority guidelines.

Published Current Guidelines on COVID-19 from Aviation Authorities

Per the Israeli Aeromedical Center COVID-19 medical screening recommendations,[34] cadet pilots fully recovered from asymptomatic or mild infection constitute a low-risk population and require only a general flight surgeon examination. Moderate and severe cases are to be grounded pending flight surgeon evaluation and specialist consultation once fully recovered. For all fully recovered military and high-performance aviators, a chest X-ray, EKG, and TTE are also required. TTE should additionally be performed for all recovered pilot cadets, regardless of flight class, who have had any documented cardiac manifestations during the disease course. Abnormal screening results necessitate cardiologist consultation and consideration of CMR.

The Canadian Armed Forces Aerospace Medicine Authority recommendations[14] state that grounded aircrew following recovery from mild infection require local clinician assessment for flight clearance, with additional screening chest X-ray and resting EKG for the following indications: cardiac examination abnormalities are found, or aircrew are partially/fully unvaccinated. Moderate COVID-19 illness requires the same workup as mild illness, plus basic laboratory investigations and exertional oxygen testing if indicated per symptomology. If infection was severe, then same as moderate illness plus TTE. Additionally, fighter pilots flying aircraft with ejection seats should either complete a dual flight prior to returning to solo, or positive G_z maneuver warm-up at the start of their first return to solo flying to ensure no respiratory difficulties.[14] Human centrifuge testing has been suggested for medically cleared pilots with recent history of arrhythmia or orthostasis prior to returning to flying high-G aircraft.[52]

As of March 2022, the AME Guide for COVID-19 asymptomatic, mild, and moderate infections allows for medical issuance for complete recovery without residual symptoms. Severe infection history or ongoing cardiovascular symptoms requires FAA deferral with subspecialty follow-up.[28]

Cardiovascular Screening Recommendations for COVID-19 Recovered Pilots

Aircraft type and setting of a pilot's flight profile must be considered by the aeromedical examiner since high-G loading maneuvers are more prone to unmask arrhythmias and overt myoepicardial injury causing hemodynamic compromise or sudden incapacitation in flight. This is further supported by prior animal studies that showed positive G_z loading can histologically lead to cardiomyocyte injury,[12,17] with less clinically pronounced in-vivo studies in human fighter pilots.[20,39,75] The aeromedical history taking should assess for symptoms of palpitations, lightheadedness, presyncope, chest pain, dyspnea, exercise intolerance, calf pain, and worsening fatigue. Cardiac physical exam should pay special attention to jugular venous distention, new murmurs, third heart sounds, popliteal and posterior tibial pulses, extremity edema, and pulse regularity. Resting 12-lead EKGs when performed are ideally compared to prior cardiographic tests since electropathologic changes seen in silent myocarditis can overlap with physiologic changes seen in athletic individuals.[98]

The following aeromedical screening considerations, summarized in **Table I**, are suggested based on comprehensive literature review for pilots seeking medical clearance with a pertinent medical history of fully recovered COVID-19 infection. Asymptomatic civilian pilots seeking Class II or Class III

Table I. Aeromedical Post-COVID-19 Infection Cardiovascular Screening Recommendations for Fully Recovered Pilots Incorporating Existing Literature Review Data, Expert Opinion, and Existing Guidelines for Aircrew Correlates Based on Flight Profile (Civilian Classes I–III, High-Performance Military/Aerobatic), Severity of Viral Illness (Mild, Moderate, Severe), Disease Course Complications, and Ongoing Post-Viral Cardiac-Related Complications.

SEVERITY OF ILLNESS/COMPLICATIONS	RECOMMENDATION
Civilian Recreational and Commercial (Class I-III)	
Asymptomatic/Mild COVID-19	Focused medical history and physical, no further cardiovascular screening in absence of infectious period complications or ongoing symptoms
Moderate/Severe COVID-19	Same for mild, EKG and chest X-ray if Class I, referral if severe infection to cardiology subspecialist for further investigations
Cardiac complications during or after infection/abnormal findings on initial examination or screening tests	Same for moderate/severe, referral to cardiology subspecialist for further investigations
High-Performance, Aerobatic and Military Pilots	
Asymptomatic/Mild COVID-19	Focused medical history and physical, no further cardiovascular screening in absence of infectious-period complications or ongoing symptoms
Moderate COVID-19	Same for mild, plus chest X-ray and EKG
Severe COVID-19	Same for moderate, TTE and serum cardiac biomarkers, referral to cardiology subspecialist for further investigations
Cardiac complications during or after infection/abnormal findings on initial examination or screening tests	Referral to cardiology subspecialist for further investigations, consider human centrifuge testing or dual-flight prior to solo flight in high-G aircraft

medical issuance regardless of COVID-19 severity stratification history, as well as high-performance, aerobatic, military, and Class I pilots with history of asymptomatic/mild infection, all require only a focused medical history and physical without further cardiovascular screening in the absence of infectious period complications or persistently ongoing symptoms. Recommendations for high-performance, aerobatic, and military pilots with history of moderate infection, and Class I pilots with a history of moderate or severe infection carry the same recommendations as previous plus an additional screening EKG and chest X-ray. Severe infection history in high-performance, aerobatic, and military pilots require same as previous plus an additional TTE and serum cardiac biomarkers. Any documented or disclosed cardiac complications during or after infection in all pilot groups, or abnormal findings on initial medical examination and screening tests, requires cardiovascular specialist consultation for further evaluation.

The established increased cardiovascular complication risk in patients having prior comorbid conditions elicits further potential consideration for commercial pilots with documented COVID-19 already holding a relevant CACI (i.e., hypertension, prediabetes mellitus) or a Special Issuance SI (i.e., coronary artery disease, diabetes mellitus, pulmonary hypertension). Consideration may also be given to temporarily restrict the asymptomatic, fully recovered post-COVID-19 pilot while actively undergoing cardiovascular screening to flying with another pilot who did not have COVID-19 or only had mild/asymptomatic infection without subsequent residual cardiovascular complications. This could provide additional in-flight safety by which any sudden incapacitation of the pilot undergoing screening could be managed by another unaffected pilot still able to fly.

Overall, a stepwise approach for AME's should be implemented in stratifying screening based on medical certificate and aircraft type:

1. Assess disease severity and classify based on the following four categories:
   a. Asymptomatic or mild (positive PCR with no symptoms or minimal symptoms treated on an outpatient basis without supplemental oxygen needs).
   b. Moderate (symptoms requiring hospitalization but not admitted to the intensive care unit).
   c. Severe (symptoms requiring hospitalization and intensive care unit admission).
   d. Prolonged outpatient recovery course (i.e., orthostasis, physical fatigue, etc.).
2. Review current pilot health status, medical class certification, aircraft type, and existing medical certification restrictions prior to COVID-19 infection.
3. Proceed with screening recommendations based on Table I. Consider additional medical evaluation or cardiology referral based on clinical judgement of the AME for any pilots holding special issuances, waivers, or CACI, regardless of pilot medical certification class or presence of cardiac symptoms.

In addition to initial cardiac screening protocol, a thorough review of all current medications and special attention to therapies administered during COVID-19 infection, including hydroxychloroquine, ivermectin, macrolides, and fluoroquinolones known for inducing cardiac electrophysiologic alterations should be documented. Recent data support continued use of ACE inhibitors,[3] beta-blockers,[22] angiotensin receptor blockers, and particularly statins for their endothelial-stabilizing and cardiovascular risk-reduction effects during and after COVID-19 illness in patients already on these drugs prior to infection.[59,85,91] No adverse lasting cardiac effects from prior dexamethasone treatment during moderate and severe COVID-19 have been demonstrated[50] and does not separately warrant concern or investigation. Continued cardiovascular physical fitness regimens for grounded pilots already cleared for regular exercise with or without medical supervision can reduce the potential cardiovascular deconditioning following illness recovery and should also be encouraged.[4,10]

DISCUSSION

Addressing the central question of return-to-duty cardiovascular screening following the COVID-19 pandemic involves several considerations such as determining accurate detection of any increased arrhythmogenic risk, which pilots require screening and to what degree, optimal screening test modalities, and occupationally relevant interpretation of screening results. In comparable cohorts such as young athletes, scuba divers, and military personnel, these guidelines have remained variable in approach considering the various clinical challenges of developing an effective strategy. Overall, it is difficult to ascertain the true prevalence of myocardial involvement due to COVID-19 infection in both the general population and airpersons since many investigations study moderate-to-severe disease in hospitalized patients, though some reviews suggest it to be relatively low. Additionally, the infectious course is not predictable, screening tests fall short in sensitivity and specificity, cost-efficacy and worktime losses must be weighed, unnecessary delay for return to duty with negative impacts on already strained operations, and relevant test interpretation requires overlapping expertise in the realm of aviation medical standards. The difficulty in ascertaining causation vs. correlation, plus the skew of more clinically severe infections occurring in elderly patients with multiple coexisting comorbidities vs. healthier patient populations confounds the ability to confidently fit COVID-19 related cardiovascular risk mitigation into the aviation standard "1% rule." Therefore, the use of this review will be highly dependent on the setting and nature of the aeromedical examiner and the evaluated airperson(s).

Cardiac dysfunction during hospitalization and pre-existing cardiovascular comorbidities do seem to prognosticate poorer outcomes, but confounding factors such as outcomes being reported mostly in hospitalized patients of older age with multiple associated risk factors makes it difficult to attribute causality or strong association with COVID-19 viral infection.

While more data are needed to understand the effects of COVID-19 on the human heart, other known viral infections such as influenza and different coronavirus strains do not typically require cardiovascular screenings in the absence of clinical cardiac-related symptoms. It is unclear whether more stringent cardiovascular screening protocols for pilots with pre-existing CACI's or Special Issuance SI's for cardiovascular-related comorbid conditions should be empirically enacted in the absence of clinically manifested cardiovascular symptoms and presence of full infection recovery.

COVID-19-related myocarditis also poses a dilemma for developing screening guidelines due to limited understanding of the significance of cardiac serum marker elevations, physiologic cardiovascular training adaptations confounding EKG and CMR findings, atypical presentation of symptoms by athletic analogs, and insufficient data to predict true prevalence and long-term effects. It is also possible that side effects of COVID-19 infection treatment protocols could have affected some of the milder reported myocarditis cases,[98] as well as other cardiac complications. Ventricular remodeling has also been confirmed to physiologically occur from athletic training and could be confused with myocarditis in fitter cohorts based on volumetric study disparities between COVID-19 positive athletes and healthy controls.[38]

Regarding return-to-play screening guidelines for athletes as a comparable cohort for high performance pilots, the recommendations from the United States of America seem slightly less pragmatic compared to European and Canadian policies,[48] the latter accounting for the growing aforementioned lack of association between COVID illness severity and risk of acquiring myocarditis. More recent appraisal of existing literature suggests a lack of data to confirm association between COVID-19 and myocarditis, leading some authors to argue against return-to-play cardiovascular screening strategies for asymptomatic and mild cases, given no randomized clinical control trials have been conducted to demonstrate utility of aforementioned cardiovascular screening tests.[1] Additionally, despite antecedent viral infection having common association with myocarditis and some other cardiac abnormalities,[53] coronaviruses have historically not been regarded as primarily cardio-trophic viruses[61] and sparse reports prior to the 2019 pandemic largely describe self-limiting cases.[80] To date regarding the current pandemic, some studies support the notion that clinically relevant myocardial injury and dysfunction are self-limiting phenomena confined to the severe illness phase.[61] Diagnosis and treatment for persistent symptoms of long-haul COVID-19 remains under investigation, currently focused on supportive care, reassurance, longitudinal monitoring, and specialist referral where appropriate.

Excessive screening with blood tests, EKG, and cardiac imaging should be avoided as much as possible, since it has a higher likelihood of false-positive findings which may be incidental at best and skews investigational studies.[78] These false positive findings would potentially require further investigation that would then unnecessarily expose individuals to risk in the form of invasive procedures and tests. More research is needed to elucidate the degree to which abnormal cardiac lab and imaging findings observed in post-COVID-19 patients bear clinical significance. Adequate pretest probability of the airpersons tested must be weighed against the limited sensitivity and specificity of existing cardiovascular testing modalities, and a practical approach to medical screening must be balanced against obtaining ideal diagnostic precision. As more COVID-19 surges and strains develop, the associated conditions will continue evolving and influence the future approach to screening airpersons. The basic principles of cardiac screening for other cardiovascular conditions such as hypertrophic cardiomyopathy, channelopathies, and coronary artery disease should not be overlooked when assessing COVID-19 recovered pilots and remains at the foundation of aeromedical cardiovascular examinations.

Several recommendations for screening fully recovered asymptomatic or mild COVID-19 cases in young, healthy populations suggests it may not be necessary, and a targeted approach based on patient symptomology is key. For history of moderate and severe infections, or patients who already experienced new cardiovascular complications while acutely ill, there is not enough evidence to exclude the commonality of patients developing heart problems. Class I pilots and military/high-performance pilots fall into this category where fitness-related sudden cardiac incapacitation poses significant risk to the pilot, passengers, aircraft, and strategic flight objectives. Thus, return-to-work screening is more strongly recommended with a combination of chest X-ray, EKG, TTE, biomarkers, cardiologist referral, and CMR when indicated based on medical history and infection severity. No criteria have yet been definitively established for diagnostic study cut offs for serum markers or imaging in the context of COVID-19 infection, and interpretation remains dependent on holistic evaluation with expert consultation on a case-by-case basis. Future observational cohorts or randomized double-blinded clinical trials may be needed to clarify the true cardiovascular risks of COVID-19 infection, its longitudinal effects, and screening protocol efficacy in reducing flight-associated medical incidents.

The findings and recommendations of this review are relevant for return-to-work cardiovascular screening protocol development for pilots after recovery from COVID-19 infection with the goal of maintaining acceptably low risk for subtle or sudden cardiac incapacitation. Aviation medical examiners should remain cognizant of the clinically apparent and occult manifestations of cardiovascular dysfunction associated with COVID-19 infection when applying return-to-work screening guidelines to ensure high flight safety standards are maintained and sudden incapacitation risk mitigated during the ongoing pandemic. Future research is needed to address gaps in knowledge regarding the cardiovascular implications of novel COVID-19 infection.

Conclusion

In summary, the major COVID-19 cardiopathology associations entail atrial (most common) and ventricular arrhythmias, myocardial infarction, nonspecific cardiomyocyte injury, atherosclerotic plaque instability, intravascular clot formation, myocarditis, heart failure, pulmonary hypertension, biventricular dysfunction, and chronic heart failure exacerbation through several plausible direct or indirect mechanisms. Syndromic persistent clinical manifestations following infection such as orthostasis, fatigue, and autonomic aberrancies which may affect pilot flight performance are common. Relevant clinical outcome data regarding viral infection support the notions that pre-existing cardiovascular disease, cardiac-disease risk factors, and severity of infection increase the likelihood for adverse outcomes of which airpersons remain a susceptible population. The ACIP, CDC, and FAA recommend COVID-19 vaccination for pilots followed by a brief no-fly period to account for the associated minimal risk profile.

High-performance analog population data largely supports existing cardiovascular screening recommendations published by the American College of Cardiology, European Society of Cardiology, Canadian Cardiovascular Society, Hellenic Journal of Cardiology, Dutch Sports Cardiology Section of the Netherlands Society of Cardiology, European Underwater and Baromedical Society, European Committee for Hyperbaric Medicine, and smaller research cohort analyses. These recommendations are reflected in existing aeromedical protocols of the Israeli Aeromedical Center, Canadian Armed Forces, and FAA and are used to present a conservative approach to cardiovascular screening following complete COVID-19 infection resolution according to flight profile. Civilian pilots seeking Class II or Class III medical issuance, as well as high-performance, aerobatic, military, and Class I pilots, with a history of asymptomatic/mild infection all require only a medical history and physical. High-performance, aerobatic, and military pilots with history of moderate infection, and Class I pilots with a history of moderate or severe infection require an additional screening EKG and chest X-ray. Severe infection history in high-performance, aerobatic, and military pilots require an additional TTE and serum cardiac biomarkers with cardiology referral.

Published literature continues to bear significant limitations and future studies should address true prevalence of myocardial involvement due to COVID-19 infection in both the general population and airpersons, further ascertaining causation vs. correlation, addressing confounders in COVID-19 cardiovascular outcome interpretation, and establishing occupationally relevant interpretation of screening results.

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Navigating Pregnancy for Employees in Civilian Rotary-Wing Aeromedicine

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INTRODUCTION: Women of child-bearing age make up an ever-increasing element of the aeromedical workforce in Australia and the UK. However, policy relating to the management of risk for pregnant employees in this sector is often missing or inadequate, with many women facing detrimental impacts on their career progression and financial well-being. For women who choose to continue flying, there is a lack of transparent guidance about the risks of flying within a helicopter in an aeromedical role. While grounding pregnant employees removes some risks, it is at the cost of autonomy and brings other adverse effects for the employee and employer. Updated reflections on this important topic will empower the audience to make informed discussions around pregnancy in aeromedical roles.

TOPIC: Applying principles from literature surrounding commercial, military, and medical aviation, the risks to pregnant employees and the fetus are reviewed. These risks are complex and dynamic depending on gestation and underlying medical problems; thus, individualization of risk management is of key importance. In low-risk pregnancies, incapacitation risk is below the usual threshold adopted for safety-sensitive aviation activities. Based on available evidence we have quantified risks where possible and provide guidance on the relevant factors to consider in creating a holistic risk-management framework. The greatest unknown surrounds the risk from vibration, noise, and winching. These are reviewed and suggestions given for discussing this risk. We also highlight the need for policy providing acceptable nonflying options to remove the pressure to continue flying in pregnancy.

APPLICATION: Based on a literature review we have generated a framework for understanding and assessing risk relating to pregnant employees in the aeromedical sector. This is intended for use by aeromedical organizations, pregnant employees, and their treating medical practitioners to provide rational and sensible policy and guidance.

KEYWORDS: pregnancy, aeromedicine, risk assessment, rotary-wing aircrew, occupational health.

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Women have been members of the aviation team since the early 1900s, but have had limited access to many roles. The current generation are now able to do all jobs in aviation, but inequity remains about normal lifestyle choices, including pregnancy. As the number of women working within the aeromedical sector increases, a pregnancy occurring is becoming a 'normal phenomenon' within the working environment. However, within the United Kingdom and Australian civilian aeromedical services, there is a widespread lack of policy to lay out a logical and standardized approach to assessing the risk of pregnant employees flying. This leaves employees unequipped to assess the risks and make an informed decision about flying duties, and leaves employers at risk of not providing an equitable working environment.

This paper aims to challenge current practice in the aeromedical sector in Australia and the UK, and question the decision-making around women working while pregnant. The fact that women are continuing to fly with any additional pregnancy

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risk implies the existence of factors, including delayed career progression, financial penalties, or cultural norms, together with inadequate policies and no structured approach to discussing the risks, motivating this decision. It is of paramount importance that a decision to cease flying duties is supported by employers, unions, and workplace culture in such a way that women are truly empowered to make a decision without experiencing negative career or financial outcomes.

This paper seeks to outline a sensible and structured approach to an occupational risk assessment, to frame the discussion, and enable a process akin to informed consent regarding the potential risks that could occur. We break the considerations around flight risk and pregnancy into four main areas: operating environment, operational role, physical pregnancy changes, and fetal influence, and discuss how these change during the pregnancy. This is a novel categorization separating aviation factors that are modifiable (relating to platform and operations) from nonmodifiable (relating to working at altitude), and pregnancy factors related to physical changes from physiological and pathological changes.

Discussion points have been drawn from several countries to highlight the disparity in approaches and to demonstrate differences between aeromedical retrieval services. Anecdotal examples from Australia and the United Kingdom represent the authors' own experience while other evidence is drawn from the United Kingdom, Australia, and the U.S. military. The authors intend this review to support discussions between employees and employers, help current and future policymaking, and highlight gaps in the evidence, with emphasis on the pressing need for research in this area. Given the limitations of the literature, this paper is not intended to provide blanket conclusions about the safety of flying while pregnant, but to provide a structured way of discussing risk between the organization and the employee to inform and support decision making.

The authors acknowledge that the role of aeromedical services and their aviation platforms varies worldwide. The scope of this paper is limited to civilian services, specifically rotary-wing platforms, delivering emergency medical care to prehospital scenes and unscheduled interfacility retrieval of patients. Although many aeromedical retrievals are done by fixed wing aircraft, the paper will not deal with these platforms. The risks discussed are those relevant to the flying crew: paramedics, doctors, nurses, winch operators, and pilots. When we discuss a pregnancy, we are including the embryonic and fetal stage up until birth. We acknowledge that there are also considerations for the employee postpartum, e.g., return to work and breastfeeding; we are focusing this paper on the pregnancy period. We also wish to acknowledge those women who choose not to fly, or continue, and suffer a complication and the psychological and emotional sequalae. The crux of informed consent is that the decision to expose oneself and a pregnancy to any risk must be made with the best available evidence, including knowledge of uncertainty, and without any form of pressure to accept flying duties.

We hope our paper is useful in three ways. Firstly, in providing information to allow occupational health practitioners to make risk assessments for pregnant employees and provide informed consent in decisions about flight duties. Secondly, in creating a framework for employers to begin writing policies for approaching the management of pregnancy for their employees. Finally, as a call for research directed at better understanding the risks to a pregnancy of rotary wing operations.

BACKGROUND

It is a decade since a literature review first explored the complex issues surrounding women flying while pregnant in the aeromedical world.[53] Since this review, despite great advances in medical work provided by such services, there remains a lack of evidence-based policy to support decision making about pregnancy within UK and Australian aeromedical services. Furthermore, civil cases like Plaintiffs v. Frontier Airlines show women face restrictions and difficulties even after giving birth.[55]

Given a lack of clear information around the risks associated with pregnant women flying in civilian helicopters, and in an era of increasing litigation, it is tempting for employers to simply remove pregnant employees from flying roles. While doctors and paramedics may have their jobs transferred to ground-based roles, these rules can severely delay career progression for those dependent on their number of flying hours or mission numbers. Often deciding to have a family coincides with a critical point in their career as they transition into highly skilled and valued members of the workforce. No pregnancy or journey is identical and, medically, it may be appropriate for a woman to stop flying duties. In the context of a long flying career this may be a brief period; however, the decision must be made with a thorough consideration of the associated risks. Pregnancy occurring needs to be normalized and a progressive approach to pregnancy should become the norm, with input from the employee, employer, rota coordinator, aircrew medical examiner, and obstetric care team. A lack of support for choice relating to pregnancy and flying could deter women entering these jobs and risks perpetuating bias toward and stigma surrounding pregnancy for aeromedical employees.

Historical concerns within rotary wing civilian aeromedical work have been based on evidence that has come from the commercial sector. Current culture in many UK and Australian services results in women ceasing flying once they declare their pregnancy. This is either because there is a policy at the service that grounds pregnant employees, or because the policy is so gray and uninformative that the women feel there is not enough information or evidence to make an informed choice. There are also no national guidelines specific to aeromedical operations. This approach is fast becoming outdated and unacceptable. With female employees now representing a considerable proportion of the sector, they need to be involved in decisions around their life and career choices. There are also widely documented benefits to maintaining a diverse workforce and a key method to achieve this is to support women when making career and life choices associated with their pregnancy. No pregnancy is the same, including subsequent pregnancies, so a clear understanding of the risks is needed to enable both employee and employer to make informed, considered, and mutually beneficial decisions.

Current Regulations

Aviation authorities around the world have different regulations covering pregnant pilots which employers must follow, together with further risk control policies as appropriate. The U.S. Federal Aviation Administration permits flying throughout a low-risk pregnancy, in accordance with FAR 61.53, unless medical requirements cannot be met. Realistically, many are transitioned to desk roles within permissive organizations around the 30th week.[45] The UK Civil Aviation Authority permits a pilot to fly as part of a multicrew operation up to 26 wk, providing it has been deemed a low-risk pregnancy by a medical examiner.

The Australian Civil Aviation Safety Authority (CASA) requires a license holder to ground herself as soon as pregnancy is confirmed and seek advice before returning. She can resume flying duties provided the pregnancy is uncomplicated and the Designated Aviation Medical Examiners (DAME) and obstetrician agree, but only until the end of the 30th week of gestation. Reinstatement requires the DAME to certify a full recovery following delivery or termination.[1] This guidance is less specific than the United States and United Kingdom but does allow more consideration of the individual. A risk assessment is made along with surveillance checks every 2 wk.

International Civil Aviation Organization Class 1 Medical Standards recommend pregnant applicants be assessed as unfit unless obstetric evaluation and continued medical supervision indicates a low-risk pregnancy.[50] For applicants with low-risk uncomplicated pregnancies, suitably evaluated and supervised, flying should be limited to from the end of the 12th week (a stage at which the pregnancy can be confirmed as low-risk) until the end of the 26th week of gestation (second trimester only).

The U.S. Air Force has adopted a permissive stance, stating that "aircrew may voluntarily request to fly during pregnancy and no waiver is required to fly in the second trimester with an uncomplicated pregnancy." While military flying introduces different risks to aeromedical work, there is clearly scope to update policy and lift historical restrictions on women flying during their pregnancy.[10]

Pilots are governed by strict rules depending on the country; however, there is not clear guidance for the rest of the crew. The rest of the paper will discuss how to consider risk and apply these principles to each crewmember. It is reasonable to consider multiple factors relevant to each individual case, with regular reassessment at check-up appointments, such as the 2-weekly review approach used by the CASA, but this level of care may not be available as part of routine antenatal monitoring.

Calculating Risk

Within aviation, the level of acceptable risk is set by the regulator and any condition that affects fitness to fly may incur a safety limitation; like any major medical condition, pregnancy is approached as a risk that must be assessed. This contrasts to most nonaviation scenarios, where a pregnant woman decides on the risks she is willing to take for herself and her pregnancy. The established principle of the 'risk triad' should be applied to assessing risk: what is the risk to the pregnancy? What is the risk to the woman—physically and psychologically? What is the risk to the operation? Clearly, there will be circumstances where not all of these align, and, therefore, a discussion of the balance of risk and the principle of 'as low as reasonably practicable' should be employed. However, where previously employers have made these decisions on behalf of women, this paternalistic approach should change and these discussions should be transparent and allow women to be involved in shared decision making.

Aeromedical work involves a reliance of each team member on the other for the safety of the group, operation, and the patient. There is a complex ethical argument about individual team members having responsibility for assessing each other's fitness to fly, although this debate is beyond the scope of the paper.

Incapacitation risk describes the sudden inability to perform tasks relevant to the mission and will, therefore, impact mission success. There are clear examples of pathological pregnancy occurrences which can cause complete incapacitation, e.g., ruptured ectopic pregnancy and placental abruption. These must be considered in the risk management process, together with the probability of occurrence at each stage of gestation and potential mitigation strategies. These events are singular; however, cumulative risks also exist such as incapacitation from sudden severe nausea and vomiting, which can happen more than once.

Quantifying risk in pregnancy is an evolving process; different physical, physiological, and psychological factors influence risk at each stage of pregnancy. The '1% rule', derived from cardiac event risk stratification,[51] is often used in aviation to provide a line of unacceptable risk of complete incapacitation.[36] This approach can be difficult to apply, especially when considering partial incapacitation, though tools such as operation risk matrices clarify the process.[12] The unquantifiable risks within aeromedical work, including large unknowns, make it difficult to provide evidence-based discussion about continuing to fly.

It is also important to consider the psychological risk to pregnant women. There are conflicting pressures on them, both internally and externally. These women are often at the height of their careers and will be acutely aware of the impact of time away from flying. However, they may equally feel peer pressure to continue flying in the face of more liberal policy for pregnant women. There is also great potential for guilt if they do decide to continue flying and a pregnancy complication occurs. This must be thoroughly explored in the risk assessment process, as the sequelae of a complication following a choice to accept a risk are potentially severe.

FACTORS AFFECTING RISK FOR PREGNANT EMPLOYEES IN THE AEROMEDICAL SECTOR

Much emphasis in the assessment of risk for pregnant aviators is placed on differentiating "low-risk" pregnancies from those that are not low risk. While wording differs by jurisdiction, anything other than "low-risk" pregnancies will likely prompt suspension of flying duties. This differs from "complicated," which is medical terminology. For example, CASA states if the pregnancy is complicated, the woman should be grounded until assessed and have regular assessments if flying duties are permitted to resume.[1] In addition, discussion should consider the context of the pregnancy, for example, the difficulty of conception, as this can be highly relevant to any discussion of risk of pregnancy complications.

While previous literature has categorized risk into 'impact of pregnancy on flying' vs. 'impact of flying on pregnancy', we present a novel approach to considering this interaction in the inherently complex aeromedical environment by breaking the considerations into four key domains: operating environment, operating role, pregnancy changes, and fetal influence—but clearly there can be some overlap between the sections. **Fig. 1** provides an overview of this categorization.

Operating Environment

These factors are risks of where the mission is undertaken, are nonmodifiable, and all crew are exposed to the same risk.

Hypoxia. The percentage of oxygen in inspired air is constant, but the partial pressure falls with increasing altitude from 20.9 kPa at sea level to 13.3 kPa at 9843 ft (3000 m), reducing the oxygen content of blood in the woman and fetus. Altitude is a cause of preplacental hypoxia and acts as an independent risk factor for low birth weight.[8] Even acute and brief exposure to hypoxia has been shown to reduce birth weight and interfere with organogenesis.[18] Pregnant women, particularly in the later stages of pregnancy, are more at risk of hypoxia due to reduced residual lung volume (due to increases in lung water and compression from the developing fetus) and increased oxygen demands. However, aeromedical missions rarely fly to significant altitude and the degree of hypoxia encountered during travel at commercial aircraft cabin altitudes [up to 4921–7874 ft (1500–2400 m)] is not considered to pose a hazard in this setting to the woman,[13] although if there a pre-existing placental disorder then the pregnancy may not tolerate hypoxia. Oxygen is available if that height is transiently exceeded; furthermore, there is dialogue among the crew as to an appropriate height to fly as this is relevant to the medical component of the mission.

Cosmic and occupational radiation. Historically there has been significant anxiety within the aviation community about the risks of cosmic radiation to the developing fetus (particularly during organogenesis at 3–8 wk), raising concerns about congenital abnormalities, growth restriction, developmental disorders, and higher miscarriage rates than the general population.[7] Other studies suggest it could interfere with a woman's menstrual cycle, causing higher rates of subfertility,[24] although this may be confounded by shift work and stress.[2] Data from survivors of nuclear weapons suggests single doses greater than 300 mSv induce deformities, with doses below 100 mSv unlikely to cause demonstrable harm.[15,38] The International Commission of Radiation Protections recommends occupational radiation exposure be limited to 1 mSv[38] and assessment of radiation exposure and methods to reduce or avoid it are legal requirements.

The U.S. National Institute for Occupational Safety and Health suggests "Try to reduce your working on long flights, flights at high latitudes, or flights which fly over the poles."[38] Exposure to electromagnetic radiation, from sources such as radar and aircraft radios, is below legal requirements for civilian jurisdictions. While noting the original studies are based on data following acute rather than cumulative exposure, the literature suggests aeromedical operations would expose

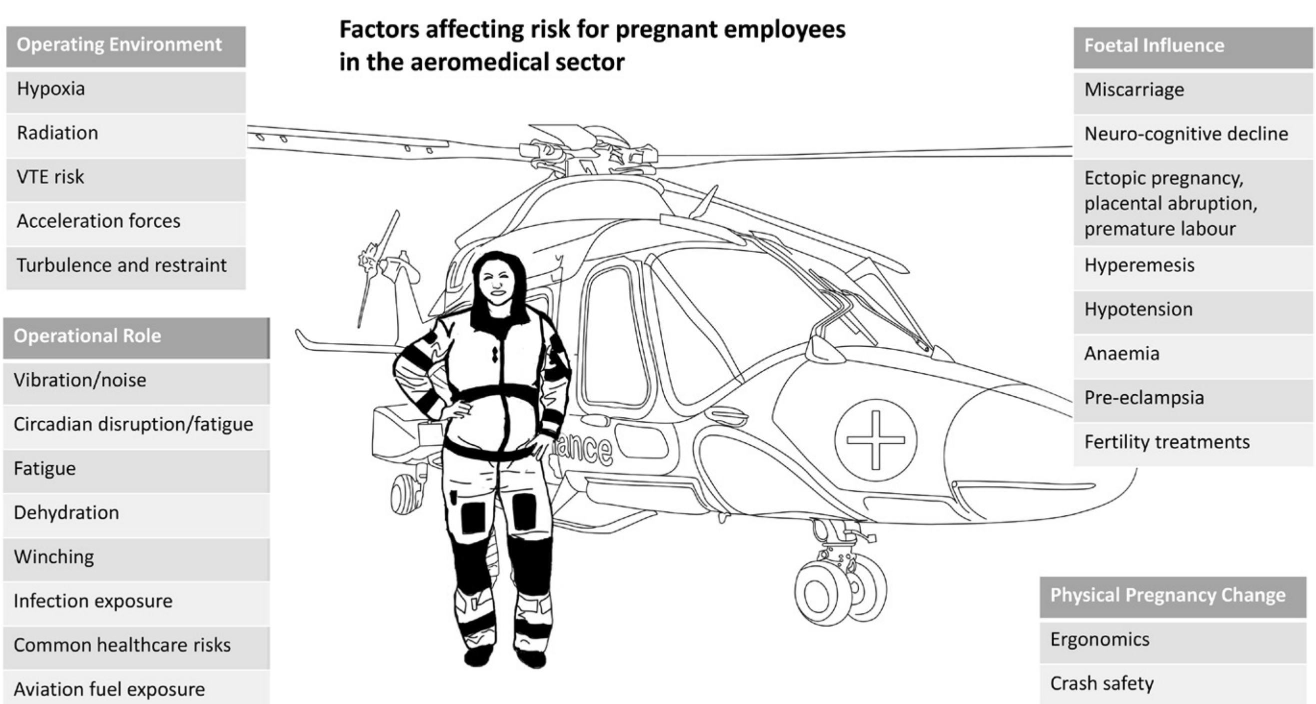

Fig. 1. Factors affecting risk for pregnant employees in the aeromedical sector.

pregnant employees to less radiation than commercial long-haul work due to the typical time spent flying and altitude. Future research could include measuring radiation exposure of aeromedical crew to increase understanding of actual radiation exposure for the aeromedical employee. In aeromedical rotary wing platforms, the nonionizing radiation risk from radio equipment is negligible due to certification requirements.

Thromboembolism. Pregnant women are at higher risk of thrombosis for several reasons, including reduced venous return and mobility, and increased estrogen levels, and this increases with gestation, with the highest risk during delivery and postpartum. There is wide variation in estimated incidence rates for deep vein thrombosis and pulmonary embolism, and although it is rare, it is the major cause of preventable maternal death.[32] The aeromedical operating environment may add risk if dehydration and prolonged periods sitting in a cramped seat occur, with risk known to double in flights over 4 h.[54] CASA address this risk through regulation requiring all pilots to have a medical investigation if they develop symptoms of thromboembolic disease such as pain in the calf or sudden shortness of breath.[30]

Acceleration forces. The body is affected by acceleration forces in different planes. An avoidance maneuver within the scope of aeromedical retrieval may expose the crew to up to 3 G sustained (4 G peak), although a standard 60° turn will not exceed 2 G (double perceived weight). Human tolerance of acceleration forces depends on factors including magnitude, time applied, direction of action, and posture of the body.[46] High acceleration is not recommended in pregnancy as the uterus will move under proportionally increased acceleration force and can result in placental abruption (as seen in high-speed trauma).

Turbulence and restraint. Aeromedical operations are time-critical and often occur in marginal weather conditions. The flight environment is hazardous to unrestrained occupants and, since pregnant employees are at higher risk of trauma from blunt force, unrestrained time should be minimized or avoided altogether. Furthermore, the pregnant abdomen places extra pressure on a 5-point harness, which may compromise the employee's comfort. In the event of exposure to significant force from turbulence or emergency procedures such as a hard landing, or even more innocuous trauma like slipping on hard ground, pregnant women should be encouraged to seek attention and appropriate monitoring for risk of placental abruption.

Operational Role

These factors are dependent on how the mission is undertaken, are potentially modifiable, but affect different members of the crew.

Vibration. Vibration and its impact on humans within a helicopter are well understood, but assessing the risk for a pregnant woman and fetus is more complex. Vibrations from a helicopter are transferred as mechanical energy to a human body, some of which is lost as heat within tissues, but internal organs are most at risk due to differences in resonant frequency. If vibrations are insufficiently dampened by other tissues or fluids, then damage can occur. In a sitting position, vibrations are dampened to a significant degree by the buttocks and the vertebral column, although this pathway is affected by body position.[22] As pregnancy progresses so does the woman's biodynamics, changing the normal pathway. Any additional injury would compound the musculoskeletal pain in the lower back experienced during pregnancy.[20] Vibration studies on female truck drivers suggests the mechanical effects on body segments is dependent on the location, frequency of vibration, and stage of pregnancy.[47] Animal studies trying to quantify the natural frequency of a pregnant abdomen and the fetus are inconclusive, although significant levels of 'whole body vibration' have been linked to fetal abnormalities and early miscarriage.[43] A recent cohort study from Sweden suggests pregnant women experiencing moderate-high exposure to vibration within acceptable 'safe' limits have an increased risk of preterm birth. Methods of reducing vibration within the helicopter include dynamic vibration absorbers, selective seat isolation, and maintenance of mechanical parts. However, beyond attempts to reduce vibration to an individual's seat, not much can be done by individual services to reduce the pregnant employee's exposure. Uncertainty surrounding this issue makes it difficult to produce meaningful policy/guidance for pregnant employees. This is clearly an area requiring more research given the significant magnitude of the risk.

Noise. Fetal hearing is considered sensitive to external sound by 27–29 wk gestation.[9] Noise exposure above 85 dB (the level of exposure requiring UK employers to provide hearing protection) may cause fetal harm, increasing the risk of low birth weight, fetal malformations, preterm deliveries,[5,9] and high frequency hearing loss in children with an increasing risk of gestational hypertension.[5,9] These levels are frequently encountered in rotary-wing operations, with significant potential morbidity for affected children.[5,39] Maternal hearing protection provides no fetal protection and consideration should be given to avoiding noise exposure from the later stages of the second trimester to minimize these risks.

Circadian disruption. Aeromedical work never stops. Shift work can have long-term health effects, including reduced immune function, increased risk of cardiovascular disease and mental health issues, and decreased cognitive performance.[28] During pregnancy a woman requires more sleep at different stages and hormones like progesterone and cortisol can worsen sleep quality, while circadian disruption has been linked to a higher incidence of miscarriage.[25] Notably, this has been recognized in legislation such as the German Maternity Protection Act, which provides relief for women from working disruptive shift patterns during pregnancy.[35]

Fatigue. "Fatigue during pregnancy is a physiological, psychological, and potentially pathological condition of decreased energy."[3] Fatigue appears inevitable during pregnancy, often worse during the first trimester due to hormonal changes and in the third trimester because of the burden of weight gain and increasing fetal metabolic demands. Around 40% of U.S. women report poor sleep quality at 14 wk gestation and this worsens with gestation. Circadian pattern disruption occurs as a result—over 40% of pregnant U.S. and New Zealand women report daytime sleepiness requiring a nap.[32] This disruption decreases cognitive performance in pilots,[28] and the same theory can be applied to other aircrew. The compound effects of fatigue and stress have been linked to various maternal and fetal complications.[25] Given the fluctuating nature of stress and sleep within aeromedicine, it would be wise for the pregnant crewmember and her service to consider the impact on rostering.

Dehydration. Heat stress in the operating environment leads to increased insensible losses. The operational environment can impede ability to maintain hydration with reduced chance for breaks. Hydrating may be avoided to mitigate limited access to private toilet facilities, increased effort with one-piece flying suits, and additional aircrew equipment. This is before pregnancy potentially increases losses from hyperemesis and frequency of urination through bladder pressure from the gravid uterus. Relative dehydration can increase the frequency of hypotension (and thus syncope),[21] mood lability,[1] and cognitive effects,[26] potentially affecting flight performance, and pregnant women should be encouraged to ensure adequate hydration.[27]

Winching. Winch rescue is a high-risk operation with safety dependent on a complex system and team members in safety-critical roles. While the actual operation differs between services, there are several noteworthy risks. The pilot holds the responsibility of ensuring the helicopter hover stays steady, the winch operator controls the exit and descent of the doctor/paramedic, and the latter need to carry the equipment down, stabilize the patient, and communicate with the onboard crew for extraction. While on the wire the crew are potentially exposed to direct trauma from striking ground objects even in normal operations, together with abnormal conditions associated with emergencies. A key safety feature is a correctly fitting harness, but this still exposes a pregnant employee to an undetermined force on their abdomen. Then there are the strains of maneuvering a patient, often with relatively austere ground support teams. A less dangerous but more frequent risk exposure is the potential for crew to be left in a remote place for hours or even days in the event of a change in weather conditions; even in low-risk pregnancies this could prove a significant concern. It may not always be operationally feasible to avoid these risks so it should be considered in discussions between employees and employers.

Exposure to infections. Pregnant aeromedical crew, as in all healthcare settings, may be exposed to infections that could be dangerous to both the mother and the pregnancy—either from the respiratory route or needle stick injuries. Any pregnant employee should have her vaccination status checked and be advised of scenarios to avoid.

Common healthcare risks. Other risks that are common to other healthcare settings which may affect the medical crew come from direct interaction with the patient and their family. All crew should be aware of handling and moving protocols to reduce the likelihood of musculoskeletal injuries. However, ligament laxity and altered biomechanics in a pregnant woman will increase the chance of these occurring, which could be a risk if the aeromedical service requires the employee to carry heavy loads. Trauma from patients and family members could also occur—a risk assessment of the mental status of any accompanying helicopter passengers should be undertaken prior to boarding.

Exposure to aviation fuels. The turbine-engine helicopters generally used in aeromedical operations burn kerosene-based fuels, commonly JP8 (U.S. military) or Jet A1. Exposure to aviation fuel has been linked to negative health effects depending on length of exposure, whether the fuel is in fume or liquid form, and how the exposure occurred (ingested, inhaled, or absorbed via the skin). Postulated negative health effects range widely across the body systems along with potential impacts on DNA and metabolism.[34,49] A study by the U.S. Air Force exploring the effect of jet fuel on pregnancy showed pregnant mice exposed to similar levels as flight line personnel demonstrated a long-term detrimental effect on the immune system of newborn (particularly male) mice. Further studies have suggested that while exposure to JP8 prior to and during pregnancy does not impact pregnancy rates, gestational length, or viability, the offspring had significantly reduced body weight compared to controls.[40] The Australian military allows female employees to exclude themselves from working with fuel due to concern regarding fertility. Finally, there is the potential for exposure to other aviation fuels containing lead and exposure to combustion products from aircraft engines.

Pregnant Crew

These factors include the physical changes of pregnancy and the effect on the ability to undertake safety procedures.

Ergonomics. Men and women can change anthropometrically throughout their career, irrespective of pregnancy, impacting functionality inside the helicopter and the ease of exit in an emergency. Harnesses have a variety of adjustments according to size and pressure point requirements, and the seats can move forward and back, allowing for changes in abdominal size when accessing the cyclic control. Adjustments aside, if an abdomen prevents full access to the controls or a comfortable restraint, there is a safety issue. Additionally, there are requirements to carry and lift heavy equipment, often at speed, which may be affected by pregnancy. This is also applicable to the fixed wing or road environment. Fixed wing aircraft may have bigger, more comfortable seats, but are usually undertaking longer missions. Road ambulances provide greater flexibility as the cabin space is bigger and stops are possible.

Crash safety: emergency egress and restraints. Catastrophic crashes in aeromedical helicopters are incredibly rare due to the safety systems required by regulators. As such, the additional risk for a pregnant crewmember is inconsequential compared to the rest of the crew. Some safety features are affected during pregnancy. Diving is not recommended during pregnancy due to the unknown risks of microscopic gas emboli[48] and, thus, any Helicopter Underwater Escape Training (HUET) requirements and/or training would also be of increased risk to pregnant women, especially with use of emergency breathing systems (EBS, compressed-air bottles for underwater escape). As a flow-on effect, any overwater operations would also be at increased risk due to regulatory requirements for HUET training and use of EBS in a maritime environment. Ensuring appropriate fit of personal protective equipment including restraints is essential for reducing risk in the event of a crash. Studies based on motor vehicle crashes show that the shoulder harness and correctly fitting lap belts are the key factors in reducing the risk of placental abruption.[6,23,42] Both restraints are already incorporated into the helicopter aeromedical restraint design, as well as training for correct fit and emergency egress procedures held annually. The risk of accidents while working in road ambulances must also be considered in minimizing risk for pregnant employees, as it does come with an increased risk of obstetric complications such as placental abruption and uterine rupture caused by seatbelts in the event of a crash,[37] although that is reduced using modern 3-point seatbelts.[17]

Fetal Influence (Physiological/Psychological Changes)

These can cause an acute incapacitation and the presence of any of these will mean the pregnancy is no longer uncomplicated.

Miscarriage. On average, 1 in 4 pregnancies result in miscarriage by the fourth week, with rising risk with maternal age.[31] There is anecdotal evidence of increased miscarriage rates within aeromedicine,[53] but this is open to significant confounding. There are often minimal warning signs, but commonly spontaneous miscarriage is preceded by abdominal cramping and bleeding. Possible causation has been linked to cosmic radiation,[7,11] sleep deprivation,[25] and physical work strain.[28] Symptomatic women should seek medical help immediately and cease flying until resolved. If there is a threatened miscarriage, then there should be a discussion with the obstetrician about what level of duties the woman should undertake.

Neuro-cognitive decline. Increased forgetfulness and poor memory are difficulties frequently experienced by pregnant women.[4] Studies on memory function in pregnant aviators are limited and very small-scale,[44] making it difficult to draw broad conclusions.

Ectopic pregnancy. Occurring in 1–2% of pregnancies, this remains the most common cause of maternal death in the first trimester in the western world. Risk factors for developing an ectopic pregnancy include previous ectopic pregnancies, fallopian tube surgery, sexually transmitted infections, pelvic inflammatory disease, fertility treatment, indwelling intrauterine device, smoking, and increasing age.[19] Early symptoms often occur as the ectopic fetus grows, which would require further investigation, but rupture can cause life-threatening bleeding, which would create an aviation emergency. Any pregnant crewmember with a history of ectopic pregnancies should be aware of the increased risk and discuss possible amended duties until ectopic pregnancy is excluded.

Hyperemesis. Nausea and vomiting occur in approximately 80% of pregnancies during the first trimester. For the majority it is mild and self-limiting, but can persist to 22 wk in 10% of cases and, in severe cases (2%), can necessitate hospitalization for intravenous rehydration. It is reasonable to assume this 'incapacitation risk' is individual and should be assessed on a case-by-case basis. Even without vomiting, nausea can still affect attentiveness at work, with up to 65% of pregnant women reporting inattention when suffering morning sickness.[32] The CASA specifies that the presence of morning sickness represents an 'unstable symptom' and would need risk assessment. The onset is unlikely to be sudden or without warning, but places responsibility on aircrew to withdraw from flying if unable to carry out duties safely. If a woman is unwell enough to require ongoing medication or hospital admission, this would be incompatible with flying duties.[52]

Hypotension. Blood pressure begins to fall during the first trimester and reaches a nadir during the second due to dilation of blood vessels and diversion of blood to the uterus. Transient symptoms such as dizziness may not hinder a pregnant woman working, but syncope causes sudden incapacitation and is an aviation emergency for a pilot. Hypotension has also been linked to a pilot's reduced tolerance for acceleration forces,[16] which can be further exacerbated by dehydration.[41] Symptoms on the ground necessitate a blood pressure check before recommencing duties.

Anemia. As the blood volume rises during pregnancy, the concentration of hemoglobin drops and, as a result, a dilutional anemia develops. This may go unnoticed or can present with dyspnea, fatigue, and arrythmias. If a pregnant team member develops these symptoms, further investigations are required. Often, simple oral iron supplementation will be sufficient to continue working, but refractory anemia may prompt a restriction to flying duties.

Pre-eclampsia. The current definition is hypertension developing after the 20th week in pregnancy accompanied by one or more signs of organ dysfunction.[29] The pathogenesis of pre-eclampsia is complex and poorly understood, although stress, which is unavoidable in the aeromedical sector, has been implicated. Pre-eclampsia can become a sudden incapacitation risk if it develops into eclampsia, albeit rare without diagnosed pre-eclampsia. Women with pre-eclampsia or pregnancy-induced hypertension no longer have 'low-risk' pregnancies.

Controlled pre-existing hypertension will require monitoring throughout pregnancy but should not preclude flying.

Placental abruption. Minimal trauma or sudden accelerating forces can cause placental abruption, which is an obstetric emergency. G force applied in flight during an emergency egress is a risk for abruption,[11] and is associated with turbulence, windshear, vortex ring states, engine loss recovery, or aborted takeoff. Although most aeromedical work does not require sudden accelerating/decelerating forces, there may be unpredictable sudden descent. Any woman with a 'high risk' pregnancy should discuss this potential complication with their obstetrician.

Premature labor. There are many causes of premature labor, but if the woman experiences bleeding or cramping then she should seek immediate medical advice and not fly.

Fertility treatment. In 2018, 54,000 women underwent assisted fertility procedures in the United Kingdom.[14] Fertility decreases with age and female physicians often delay childbearing due to the burden of their careers.[33] Increased use of IVF treatments should be recognized and normalized in policy. As IVF automatically classifies a resulting pregnancy as complicated, additional psychological factors may reduce the desire to continue flying. There exists no literature regarding IVF treatments and flight safety, thus all crew should be aware of requirements within their local jurisdiction for discussing changes in medications with their aviation medical examiner.

DISCUSSION

Pregnancy is a normal physiological process, but for women working within the aeromedical sector the risks to the pregnant employee, unborn child, and the operation must all be considered when deciding whether and how long to continue flying. As more women enter aeromedical roles, it is vital that the regulations and policy surrounding pregnancy and aviation provide support for this increasing proportion of the workforce during a normal part of their lives.

Given the additional risk of rotary-wing aeromedical work compared to not flying, the creation of a work environment where there are no costs to pregnant employees who stop flying should be the aim of both employers and unions alike. The language of policy needs to make clear that while flying in pregnancy will be supported where it meets appropriate safety criteria and the employee wishes to take the additional risk, it will never be expected, and the employer will do everything possible to mitigate the effects of not flying. Pregnant employees should be provided with the available evidence and give informed consent if they choose to continue flying. In the event of an adverse pregnancy outcome when flying duties continue, employers should be prepared to help support their employee, who faces a heavy psychological and social burden.

An important consideration is the complex issue of ownership of risk within aviation. The question of who owns risk in pregnancy is vexed, with significant crossover between the responsibilities of the aircraft operator, pilot, and individual members of the crew. Imposing flight restrictions should occur only where a demonstrable risk to safety exists that cannot be managed in less invasive ways, and unilateral decisions by employers should only consider incapacitation risk and ability to physically perform duties. While joint decision-making during a woman's pregnancy is a wider ethical discussion than this paper, the authors advocate a collaborative approach to decision-making involving the employee. The fluctuating course of pregnancy might mean that, for example, remote area operations are not safe in a particular week, where the next week they are acceptably safe. Access to an informed obstetrician and flight doctor allows an ongoing discussion which can adapt to the dynamic process of pregnancy. Clearly, stretched resources and scheduling may mean that this flexibility is not universally available, though it should be aspired to and at least some flexibility should be built into a pregnant employee's roster. Offering a more individualized work plan than dichotomized flying or nonflying roles should be seen as the optimal model for empowering pregnant employees.

Undertaking any role in the aeromedical sector usually requires 10–15 yr of experience in a career path as it requires high levels of experience and expertise. For example, pilots need appropriate qualifications and flight experience to meet the demands of the job. Most pilots have a military pedigree flying complex helicopters and considerable experience of winching, night vision goggles flight, and dynamic operations relative to total time. Similarly, paramedics will have completed further postgraduate qualifications in intensive care and spent considerable time on the road before being considered for a flight role. Doctors are often toward the end of their specialty training or practicing at a specialist level. This means most women are not entering the industry until their thirties, so, if choosing to start a family, are more likely to experience subfertility. For women, at this critical moment in their career paths, if they choose to have children, it is imperative their career progression is actively supported by the sector so that they can continue to progress in the future and use their high-value skill set. Furthermore, when applying for jobs, pregnancy-supportive approaches from employers will likely be considered by applicants.

Clearly defined policy for managing pregnancy in aeromedical operations is important not just to individual employees; it is vital for the industry as it shows commitment to investing in this high-value skill set for the long-term. Services should adopt clear policies outlining how risk will be assessed, criteria for allowing continued flying, and how nonflying duties will be handled (both by choice and medical disqualification). Consideration should also be given to preconception restrictions, if medically necessary, and return to work after delivery. This is important to allow employees to make major life decisions that balance a multitude of factors. Ultimately it will pay dividends for an employer to retain a high value asset, thereby achieving a return on their initial investment. If a woman is given a choice to fly or not through pregnancy, disruption to the workforce is minimized, as is disruption to her training and currency. However, given the significant unknowns, there is an urgent need for better evidence to guide risk assessment and decision-making. We urge employers, unions, and occupational health providers to normalize pregnancy in the aeromedical workplace, with focus on research to better understand the risks of this work while pregnant.

If a woman does not continue flying during pregnancy, there are still benefits to be gained from proactive management. When engaging in discussions with pregnant employees, an employer should encourage roles that supplement their operational knowledge. This could include management roles, further education, or application of their skills in a checking and training capacity. Such lateral thinking creates opportunities for the individual and enhances the employer's workforce diversity.

Aeromedical work differs depending on service and role and, therefore, the issues raised by this paper need to be applied on an individual basis. For example, a different approach is required by services with water- and winch-rescue elements than services performing only "land on" operations. Similarly, where longer transfers are common, the risk of fatigue and dehydration may be of greater significance. We would urge caution if allowing flying duties with tasking restrictions, as mission momentum can lead to "mission creep" and pressure to bend vague restrictions; where restrictions are established, they should be clear and known to the crew and tasking agency.

Many of the risks discussed above are applicable to any role, but it is important to closely understand the specific risks associated with each role. The aim of this paper is to highlight the current evidence base and provide a framework for understanding risk of flying while pregnant to assist aeromedical services around the world in creating their own policies.

Conclusion

This review has summarized current literature surrounding the risks of pregnancy and aeromedical work with a view to providing guidance for creating policy in this area. To summarize, we suggest the following conclusions:

1. The risks to pregnant women and the fetus are complex and dynamic, affected by gestation and underlying medical conditions. As a result, defining a generic policy to fit all circumstances is difficult. Efforts should be made to provide broadly inclusive policy with specific advice tailored to the risks of specific aeromedical roles and the individual pregnancy.
2. Work needs to be done to urgently address the career, financial, and social pressures motivating pregnant employees to continue flying during pregnancy.
3. The literature suggests women with low-risk pregnancies do not have a significantly increased incapacitation risk provided they seek medical attention if new symptoms occur.
4. Historical concerns surrounding aviation risks such as cosmic radiation and hypoxia are not relevant in low-risk pregnancies within civilian rotary-wing aeromedical work.
5. The greatest unknown risks are vibration, noise, acceleration, and winching. These must be considered in any decision to continue flying during pregnancy.
6. Policy implementation should recognize the higher need for rest during pregnancy and risks posed by circadian disruption, especially in relation to night shifts.
7. To mitigate the unknown and potential risks, a partnership between aerospace medical and antenatal care providers and the employing organization is essential. Frequent and regular antenatal checks that consider the occupational context are a sensible approach.
8. There is a pressing need for research to quantify the risks of vibration and noise on pregnancies in rotary-wing aeromedical work.

We recommend aeromedical organizations introduce a policy with a structure as outlined in this paper to allow the pertinent risks to be highlighted and facilitate discussions and individualized considerations. The holistic risk-management framework suggested within this paper will allow tailored decisions made as a team for individual pregnancies. Based on available evidence, we have quantified risks where possible and provided guidance on the relevant factors to consider in creating a holistic risk-management framework. There is limited evidence in some key areas that require further study, which we have highlighted.

It is inexcusable in 2022 for aeromedical organizations to not have policies covering operations involving pregnant employees. Introduction of policies based on the best available knowledge will encourage more women to enter aeromedical work in the first instance, support women having a family while continuing with their career, and maximize retention of highly skilled and expertly trained employees.

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Prophylactic Splenectomy and Hyposplenism in Spaceflight

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BACKGROUND: There is debate whether astronauts traveling to space should undergo a prophylactic splenectomy prior to long duration spaceflight. Risks to the spleen during flight include radiation and trauma. However, splenectomy also carries significant risks.

METHODS: Systematic review of data published over the past 5 decades regarding risks associated with splenectomies and risks associated with irradiation to the spleen from long duration spaceflight were analyzed. A total of 41 articles were reviewed.

RESULTS: Acute risks of splenectomy include intraoperative mortality rate (from hemorrhage) of 3–5%, mortality rate from postoperative complications of 6%, thromboembolic event rate of 10%, and portal vein thrombosis rate of 5–37%. Delayed risks of splenectomy include overwhelming postsplenectomy infection (OPSI) at 0.5% at 5 yr post splenectomy, mortality rate as high as 60% for pneumococcal infections, and development of malignancy with relative risk of 1.53. The risk of hematologic malignancy increases significantly when individuals reach 40 Gy of exposure, much higher than the 0.6 Gy of radiation experienced from a 12-mo round trip to Mars. Lower doses of radiation increase the risk of hyposplenism more so than hematologic malignancy.

CONCLUSION: For protection against hematologic malignancy, the benefits of prophylactic splenectomy do not outweigh the risks. However, there is a possible risk of hyposplenism from long duration spaceflight. It would be beneficial to prophylactically provide vaccines against encapsulated organisms for long duration spaceflight to mitigate the risk of hyposplenism.

KEYWORDS: prophylactic splenectomy, space travel.

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Throughout the duration of human spaceflight, there has been discussion in the literature regarding the benefits of prophylactic appendectomy and cholecystectomy to avoid appendicitis and biliary disease while in space. Appendicitis and cholecystitis are mission critical diagnoses, as they impact the ability to complete the mission for both the patient and other crewmembers.[3,26,29] There is now ongoing debate on the role of prophylactic surgery to avoid these mission critical surgical pathologies.

The spleen is extremely sensitive to trauma and radiation. Unsurprisingly, spaceflight confers risks of both trauma and radiation. Recently, the utility of prophylactic splenectomy to avoid radiation induced lymphoma from long duration spaceflight has also been questioned.[23] While the development of lymphoma following return to Earth is not a mission critical diagnosis, it still carries significant morbidity and mortality for an astronaut and may disqualify them from future missions.[7,38] Thus, a closer analysis must be completed to determine whether prophylactic splenectomy is of use to individuals traveling to space. This article will describe the risks experienced by asplenic individuals, compare those risks with risks of adverse events associated with the spleen during spaceflight, and finally, discuss whether prophylactic splenectomy is of benefit for those traveling on long duration spaceflights.

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METHODS

A systematic review of data published over the past 5 decades regarding risks associated with splenectomies, dosages of radiation leading to adverse effects on the spleen, and radiation risks experienced on long duration spaceflight was completed. Inclusion criteria included articles pertinent to pathology developed postsplenectomy, articles specifically detailing dosages of radiation received by the spleen in everyday situations, and articles reporting radiation experienced during space travel.

RESULTS

Risks in Splenectomy

Hemorrhage is the main risk during a splenectomy and immediately postoperation, varying between 12–30%. Intraoperative mortality rates secondary to hemorrhage is 3–5%. One study shows a mortality rate as high as 30% postoperatively, especially when splenectomy is performed for myeloproliferative disorders.[2,35,39] The risk of mortality following splenectomy not associated with hemorrhage is much lower, as it is with prophylactic splenectomy. Thromboembolic events occur in approximately 10% of postsplenectomy patients, which can include deep vein thrombosis, portal vein thrombosis (PVT), or a pulmonary embolism (PE). Due to the splenic vein's anatomy in relation to the portal vein, the portal vein develops into a prothrombotic state following a splenectomy. One prospective study reveals a 55% chance of PVT in laparoscopic splenectomies. On average, risk of PVT ranges from 5 to 37% postsplenectomy.[8,14,18] PEs have also been associated with splenectomies at a higher rate as compared to other surgeries.[18,22,28] Mortality from PE was associated with a relative risk of 4.53 in splenectomized patients.[22,28] In addition to venous thromboses, splenectomies carry an increased risk for arteriosclerotic disease as well. Myocardial infarction and strokes are more frequently observed following splenectomies in patients over 40 yr of age.[8]

The loss of the spleen removes the ability to fight encapsulated organisms such as *Streptococcus pneumonia*, *Neisseria meningitides*, and *Hemophilus influenza*. Most cases of overwhelming postsplenectomy infection (OPSI) occur between the second and third year after surgery.[34,36] On average, there is a 0.5% chance of developing OPSI at 5 yr postsplenectomy; however, a 42% chance of OPSI has also been observed in some populations. Mortality rates can be as high as 60% for pneumococcal infections, with higher rates seen in immunodeficient patients. While vaccines specific to *S. pneumonia*, *N. meningitides*, and *H. influenza* are regularly administered to splenectomy patients, other species can also cause OPSI. At times, sepsis and subsequent organ failure develop before vaccines are even able to be given. Other studies show higher rates of death from OPSI the farther an individual is from the operation.[11,34,36]

Due to a lack of immunologic function, splenectomy increases the rate of secondary leukemia.[31] In a retrospective study with 1094 patients, rates of cancer of any type were increased in those without a spleen. Those who developed cancer after splenectomy were also more likely to die from the cancer, with a relative risk of 1.53. While splenectomies may have originally been performed for cancer staging and alleviation of symptoms secondary to lymphomas, postsplenectomy Hodgkin's lymphoma, non-Hodgkin's lymphoma, acute myeloid leukemia, chronic lymphocytic leukemia, and chronic myeloid leukemia are seen in a handful of patients 2 to 5 yr following splenectomy.[22]

Risks to the Spleen from Long Duration Spaceflight

While there is risk to the spleen from trauma in long duration spaceflight, most traumas with high enough impact to cause significant splenic injury are likely to be fatal, as the most common cause of severe splenic injury on Earth is due to high velocity motor vehicle collisions.[17,30] Due to the hematopoietic capabilities of the spleen, the organ itself is relatively more radiosensitive compared to other intraabdominal tissues.[16,25] There is a higher likelihood of the spleen suffering from radiation induced adverse events rather than trauma in long duration spaceflight.

Radiation dosage can be measured in Gray (G_y), which describes the amount of energy that is absorbed based on body mass, and Sievert (Sv), which describes the radiation needed to harm the tissues. For the human spleen, irradiation of 1 Gy is approximately equivalent to 1 Sv.[1,27,40] An individual receives approximately 3 milliSievert (mSv) to 7 mSv to their intraabdominal organs every year from every day, environmental radiation sources.[9,19] A computerized tomography scan of the abdomen and pelvis confers 15 mSv to 31 mSv.[33] In cislunar space, crewmembers may experience radiation of 100 mSv/h during a solar particle event.[4] Solar particle events can deliver as much as 500 mSv/h to internal organs during interplanetary travel.[5] For crewmembers on the International Space Station for 6 mo, the average radiation is approximately 80 mSv.[19] The radiation exposure from a year long trip to Mars is estimated to be 662 mSv.[20]

Up to 72% of patients experienced reduction to tissue volume after experiencing 10 Sv of ionized radiation over 2 wk, or approximately 714 mSv/d.[41] The spleen was noted be reduced to 37% of its original volume with 45 Sv.[37] Irradiation decreases the immune response of the spleen due to both a decrease in mononuclear cells and its prevention of proliferation of surviving mononuclear cells. Cell populations including B lymphocytes, T lymphocytes, monocytes, macrophages, and natural killer cells all declined. For instance, exposure of 8 Sv leads to a decrease of B lymphocytes by a factor of 200. Interestingly, lineages such as natural killer cells are able to regenerate sevenfold the cell count compared to pre-irradiation tissue.[16,21] In a 2017 meta-analysis on the effects of 10 Sv of irradiation to the spleen, 3% experienced neutropenia, 28% experienced anemia, 30% experienced thrombocytopenia, 21% experienced leukopenia, and 8% experienced pancytopenia. In the review, 0.7% resulted in mortality secondary to hemorrhage from thrombocytopenia.[41]

Studies have shown that there is a proportional relationship between dose of radiation received and cancer risk.[15] However, there continues to be debate on the exact radiation dosage threshold that would induce cancer. Overall, the literature suggests irradiation between 50 mSv to 200 mSv to be carcinogenic.[4,6,32] Leukemia and solid organ malignancy have been observed to be associated with ionized radiation to the spleen. In one study involving 1391 patients, irradiation to the spleen resulted in a relative risk of 5.69 for development of non-Hodgkin's lymphoma compared to those who did not experience splenic radiation as treatment of a prior cancer.[12,13] Other studies reveal a relative risk of 3.67 of acute leukemias, myelodysplastic syndromes, non-Hodgkin's lymphomas, and solid tumors associated with 40 Sv of irradiation to the spleen over a period of several months.[10]

DISCUSSION

We must compare the clinical risks associated with splenectomies to the risks of splenic adverse events that may take place during space travel. **Table I** compares whole body irradiation dosages specific to the human spleen. If we closely evaluate **Table II**, which presents risks associated with radiation, and compare those to risks associated with splenectomies, the radiation threshold needed to induce the listed outcomes are all significantly above what is likely to be experienced on an interplanetary spaceflight. Specifically, malignancy associated with splenic irradiation is noted to have a relative risk between 3.67 and 5.69 compared to those who do not undergo radiation.[10,12,13] However, the dosage in those studies required to cause malignancy is 40 Sv; even a 2-yr round trip to Mars would not reach anywhere close to that level of radiation.

Furthermore, pathologies such as neutropenia, anemia, thrombocytopenia, leukopenia, pancytopenia, and mortality secondary to hemorrhage resulted from radiation doses in the realm of 10 Sv.[20,41] With this data, we can extrapolate that the most likely consequence of radiation from long duration spaceflight outside of low Earth orbit is likely to be mild hyposplenism.

Contrarily, those undergoing splenectomies are at much higher risks for a range of complications. During the perioperative period for instance, deep vein thromobosis (10%) and PVT (5–37%) are common, and mortality can be secondary to hemorrhage (6%) and PE (0.2–0.9%) (see Table II). OPSI rates were noted to be as high as 0.5% at 5 yr following splenectomies, with appropriate vaccination. The overwhelming infectious process is associated with 60% chance of mortality in some studies. While it takes approximately 40 Sv to see development of malignancy, splenectomy itself also garners a relative risk of 1.53 for development of non-Hodgkin's lymphoma. However, we must specify that these reported statistics are based on patients with traumatic injuries, malignancies, or some other pathology requiring a splenectomy. From a clinical perspective, elective splenectomy on a healthy individual would most likely generate lower risks.

Table I. Comparison of Whole-Body Radiation Dosages in MilliSieverts (mSv) Specific to Proton Emission Experienced by Humans.

EXPOSURE	mSv
Yearly from environment*	3–7
CT scan of abdomen and pelvis†	15–31
275 miles above Earth‡	80
Trip to Mars for 12 mo§	662
Solar particle event to internal organ¶	500
Threshold for cancer induction**	200

*Enrici et al.[12], Mohye El-Din[25]; †Smith-Bindman[33]; ‡Mohye El-Din[25]; §Brodsky et al.[7]; ¶Newhall et al.[26]; **Boerma et al.[5], Koeffler et al.[21]

It is also important to discuss the ethics surrounding prophylactic surgery. There are severe ethical issues in requiring individuals in any remote care situation to have prophylactic surgery that is not indicated for any pathology. If the procedure becomes a requirement for selection and an individual is being coerced into the procedure, it suffices as a violation of informed consent. To remove the spleen in anticipation of traumatic splenic injury or development of malignancy is not a standard of care in any civilian clinical setting at this time, and the interplanetary environment should be no exception. We cannot endorse medical or surgical practices that do more harm than good. Performing prophylactic surgery to prevent low incidence diseases is nonproductive. Moreover, a prophylactic splenectomy does not alter the overall surgical capabilities of a spaceflight medical system, which will ultimately have resources to handle surgical emergencies. As spaceflight becomes more accessible and interplanetary spaceflight becomes a reality, hyposplenism may occur; however, prophylactic splenectomy should not be performed.

As a decrease in splenic volume and function is to be expected from long duration spaceflight irradiation, efforts to mitigate this loss of function may be useful. We therefore recommend prophylactic vaccination against encapsulated organisms. Patients are given "post-splenectomy vaccines" in most clinical settings to prevent infection from encapsulated organisms after splenectomy.[24] As such, administration of prophylactic postsplenectomy vaccines may help mitigate potential risks of adverse events secondary to radiation for those embarking on space travel. The specific vaccines necessary are those that prevent infections caused by *S. pneumonia, N. meningitides,* and *H. influenza*, common species leading to OPSI, and should be given prior to long duration spaceflight.

Comprehensively assessing these risks, our recommendation is that astronauts can safely pursue long duration space travel outside of low Earth orbit without the need of prophylactic splenectomy. The use of prophylactic surgery to prevent the possibility of splenic trauma and radiation induced malignancies, which overall are of low incidence, is not an appropriate method of preparing for spaceflight and prevention of hyposplenism—the potential benefits do not outweigh the significant risks. However, the risks of hyposplenism from radiation during long duration interplanetary spaceflight are real and may be best mitigated by prophylactic vaccination against encapsulated organisms.

Table II. Acute and Delayed Risks Associated with Splenectomy and Risks Associated with Splenic Irradiation.

SPLENECTOMY RISKS	PERCENT RISK		REFERENCES
Acute Risks Associated with Splenectomy			
Splenic injury in blunt traumatic injury	23.8%		Hsieh et al.,[17] Reiff et al.[30]
Mortality associated with splenic injury from blunt trauma	33%		Hsieh et al.,[17] Reiff et al.[30]
Mortality associated with intraoperative hemorrhage during splenectomy	3–5%		Weledji,[39] Targarona,[35] Asoglu et al.[2]
Mortality associated with post splenectomy hemorrhage	6%		Weledji,[39] Targarona,[35] Asoglu et al.[2]
Deep vein thrombosis post splenectomy	10%		Ha & Arrendondo,[14] Ikeda et al.,[18] Crary & Buchanan[8]
Portal vein thrombosis post splenectomy	5–37%		Ha & Arrendondo,[14] Ikeda et al.,[18] Crary & Buchanan[8]
Mortality associated with pulmonary embolism post splenectomy	0.9%		Pimpl et al.,[28] Ha & Arrendondo,[14] Kristinsson et al.[22]
Delayed Risks Associated with Splenectomy			
Overwhelming postsplenectomy infection (OPSI) at 5 yr	0.5%		Weledji,[39] Kristinsson et al.,[22] Edgren et al.,[11] Tahir et al.[34]
Mortality associated with OPSI	60%		Weledji,[39] Kristinsson et al.,[22] Edgren et al.[11]
Malignancy associated with splenectomy*	RR 1.53†		Weledji,[39] Kristinsson et al,[22] Edgren et al,[11] Rodeghiero & Ruggeri[31]
RISKS TO THE SPLEEN FROM POTENTIAL RADIATION DURING SPACE TRAVEL	**PERCENT RISK**	**RADIATION NEEDED**	**REFERENCES**
Tissue volume reduction	72%	10 Sv	Trip et al.,[37] Harrington et al.,[16] Zaorsky et al.[41]
Neutropenia	3%	10 Sv	Harrington et al.,[16] Zaorsky et al.,[41] Koeffler et al.[21]
Anemia	28%	10 Sv	Harrington et al.,[16] Zaorsky et al.,[41] Koeffler et al.[21]
Thrombocytopenia	30%	10 Sv	Harrington et al.,[16] Zaorsky et al.,[41] Koeffler et al.[21]
Leukopenia	21%	10 Sv	Harrington et al.,[16] Zaorsky et al.,[41] Koeffler et al.[21]
Pancytopenia	8%	10 Sv	Harrington et al.,[16] Zaorsky et al.,[41] Koeffler et al.[21]
Mortality associated with hemorrhage from thrombocytopenia	0.7%	10 Sv	Harrington et al.,[16] Zaorsky et al.,[41] Koeffler et al.[21]
Acute leukemia, myelodysplastic syndromes, non-Hodgkin's lymphoma, solid tumors	RR 3.67–5.69*	40 Sv	Gilbert,[13] Enrici et al.,[12] Dietrich et al.[10]

*Malignancy associated with splenectomy was mostly determined as non-Hodgkin's lymphoma.
†Relative risk is compared to individuals without splenectomies or those who did not undergo intraabdominal radiation as treatment for other cancers.

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Just-in-time Training with Remote Guidance for Ultrasound-Guided Percutaneous Intervention

David J. Lerner; Michael S. Pohlen; Robert C. Apland; Sherveen N. Parivash

BACKGROUND: Management of surgical emergencies in spaceflight will pose a challenge as the era of exploration class missions dawns, requiring increased crew autonomy at a time when training and supplies will be limited. Ultrasound-guided percutaneous intervention would allow for the management of a variety of pathologies with largely shared equipment and training. This proof-of-concept work attempts to determine the feasibility of "just-in-time" remote teaching and guidance of a sample procedure of this type.

METHODS: Subjects naïve to ultrasound-guided intervention were instructed via a short video regarding the technique for placement of a percutaneous drain into a simulated abscess within a gel phantom. Subjects were then guided through the performance of the procedure via two-way audiovisual communication with an experienced remote assistant. Technical success was determined by the successful aspiration or expression of fluid from the simulated abscess following drain placement. This was then performed by and compared with staff experienced with such procedures. Time to completion and number of needle redirections required were also measured.

RESULTS: All 29 subjects naïve to interventional work and the 4 experienced control subjects achieved technical success. There was a statistically significant difference in the time to completion between the two groups, with the experienced subjects averaging 2 min to completion and the inexperienced 5.8 min. There was no statistically significant difference in the number of redirections.

DISCUSSION: This proof-of-concept work demonstrates high rates of technical success of percutaneous ultrasound-guided intervention in previously inexperienced personnel when provided with brief just-in-time training and live two-way audiovisual guidance.

KEYWORDS: aerospace medicine, ultrasound-guided procedure, radiology training.

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Ultrasound has a long and established history of use in spaceflight for medical diagnostics and monitoring, both aboard the International Space Station (ISS) and its predecessors.[14] The imaging modality has been implemented for evaluation of pathology ranging from optic globe flattening to venous thrombosis to renal calculi. As point-of-care ultrasound is an inherently operator dependent technique and there are limitations to crewmember training time, just-in-time inflight training has been combined with real-time guidance to enable the performance of this wide range of exams.[3] These efforts have met with success, with acceptable accuracy, consistency, and speed, despite nonphysician operators. These results are further supported by multiple terrestrial studies demonstrating effective teleguidance of ultrasound-naïve trainees for cardiopulmonary and trauma evaluation.[6,12] Entering the era of exploration class missions, with increasing difficulty of medical evacuation but similar limits on preflight training and crew size, onboard educational tools and real-time or near real-time ground-based guidance will prove increasingly vital for the continued utility of complex ultrasound evaluations.

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Management of surgical conditions in spaceflight presents numerous challenges given the resource constraints, reduced gravity, and unique pathology encountered in this environment.[2] While a surgical emergency has yet to transpire in spaceflight, data from probabilistic risk assessments based partially on analog populations suggest that medical events are more likely to occur as mission length and crew size increase.[1] Given that prophylactic surgery is unlikely to reduce mission risk, surgical techniques targeted toward these and other pathology have and will continue to be developed and adapted for use in spaceflight.[13]

Difficult resource trade-offs are encountered when dedicating personnel, training, and equipment to the task of providing inflight care for surgical pathology. Specific concerns include mass, power, and space limitations of medical and surgical equipment, technical skill to perform the procedure in microgravity with limited instrumentation, and postsurgical care including management of any potential complications. Ultrasound-guided intervention is one potential aid to many potential surgical emergencies.[11,14] Portable ultrasound probes and interventional equipment are lightweight and compact, the necessary incisions small, the recovery time short, and the complications less frequent than following open surgery. While the need has not yet arisen to perform imaging-guided interventions on the ISS, there have not been any physicians to date with formal training in interventional radiology in the astronaut program, and even in the case of formal training, skills may atrophy before their need arises. Future exploration class lunar and Martian missions may require such treatment capabilities.[4,9] The potential of ultrasound guided procedures has previously been described in the literature.[5,7,8] Among the aforementioned surgical pathologies most likely to occur in spaceflight, several either directly or indirectly possess possible sequelae amenable to palliative or curative treatment with ultrasound-guided catheter placement. These include appendicitis or diverticulitis complicated by abscess, cholecystitis, hemo- or pneumothorax, and ureterolithiasis resulting in obstruction or pyonephrosis. However, no studies to date have demonstrated that personnel without training at a specialist level would be able to successfully perform ultrasound-guided drain placement with remote guidance. We present this paper as proof-of-concept work to address this question.

METHODS

To simulate a patient with a drainable intraabdominal fluid collection, an anthropomorphic phantom was constructed by pouring human tissue density ($0.91\ g \cdot ml^{-1}$) melted ballistics gel (ClearBallistics; Lexington, SC) into a plastic mold of a human pelvis (**Fig. 1**). A cylindrical chamber in the gel pelvis was created while cooling the gel to form a void to hold a replaceable drainable fluid collection. This chamber measured 7 cm in average diameter and 5 cm in height. Once cooled to a solid, the gel was removed from the mold. A latex disposable glove was filled with water, tied at the end, and placed in the chamber in the pelvic gel phantom to simulate a drainable fluid collection. The deformable glove filled with water conformed to the cylindrical shape of the chamber. The phantom was covered with a black latex membrane to obscure the fluid collection from the operator. There were 29 participants who were selected with the exclusion criterion of having had no dedicated training placing percutaneous drains with ultrasound guidance. These procedurally naïve subjects included 4th year medical students, physician assistant students, 1st year radiology residents prior to an interventional radiology (IR) rotation, and radiology technologists (**Table I**). This study was exempted from human subject Institutional Review Board approval as the data was collected noninvasively during an educational exercise that the subjects would be reasonably expected to undertake in the future. Of the 29 subjects, 19 performed the procedure with the guiding radiology personnel within the same building but in a different room, while 12 subjects performed the procedure with the remote guidance personnel approximately 1200 km away. An additional four control participants were then selected with the inclusion criteria of being a trained physician

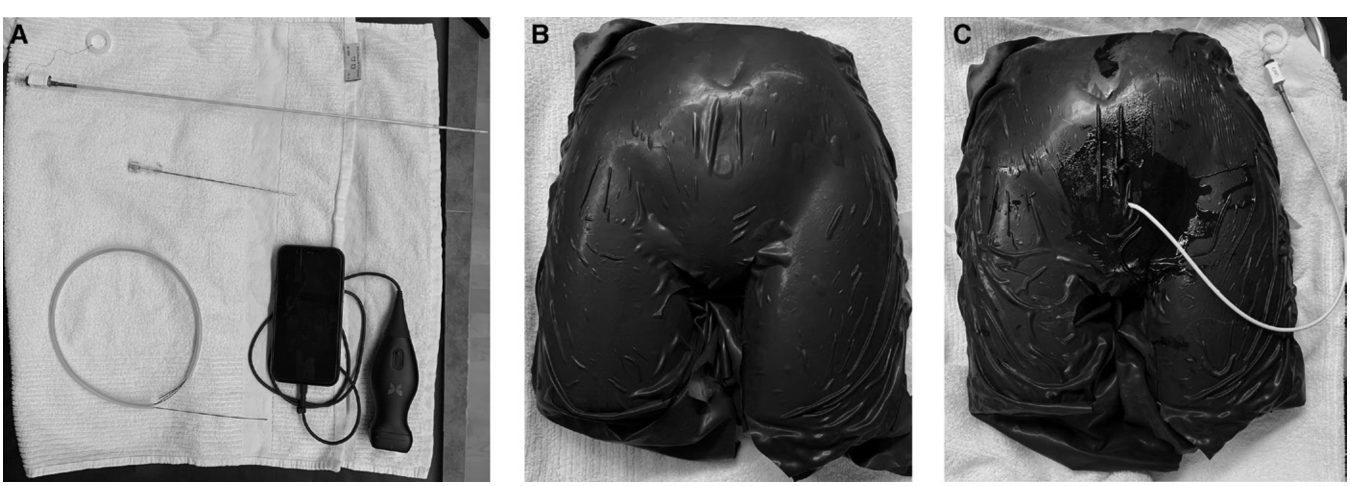

Fig. 1. Images showing the: A) initial procedure tray setup and the anthropomorphic torso phantom B) before and C) after successful insertion of percutaneous drainage catheter.

Table I. Level of Training for the 33 Study Participants.

LEVEL OF TRAINING:	NUMBER OF SUBJECTS:
Medical Student	10
Physician Assistant Student	1
Radiology Resident, no IR experience	13
Radiologic Technologist	3
Radiologic Technologist Student	2
IR-trained Physician Associate (control)	1
Attending Radiologist (control)	3

associate or attending radiologist who regularly performs ultrasound-guided procedures. These four subjects performed the simulation without assistance or remote video guidance.

The procedurally-naïve participants were first shown a 5-min tutorial video demonstrating the use of the ultrasound probe to visualize the fluid collection within the phantom and how to subsequently place a drainage catheter in stepwise fashion within the fluid collection using a 17G introducer trocar needle, a 0.035" or 0.038" guidewire, and a #10 French pigtail percutaneous drainage catheter. After watching the video, participants were placed in an exam room alone which contained a portable ultrasound probe and monitor, the pelvic phantom with preloaded drainable fluid collection, a procedure tray containing the same instruments used in the tutorial video, and a laptop/webcam connected to a two-way video call with a radiologist in a separate location. The radiologist guiding the procedure possessed fellowship-level procedural training experience. The ultrasound equipment used included a Butterfly iQ at site one (Butterfly Network, Guilford, CT) and an ACUSON S2000™ Ultrasound System, HELX™ Evolution, at site two (Siemens AG, Munich, Germany). Participants then attempted to place the drainage catheter within the fluid collection using remote assistance in a stepwise fashion as follows:

1. The participant scanned the phantom with the ultrasound unit.
2. Upon confirmation of successful target fluid collection identification by the radiologist, the participant was instructed to pick up the introducer needle and insert it a short distance into the phantom toward the target in the plane of the ultrasound probe.
3. The needle was advanced slowly in a stepwise function by the participant with the radiologist approving the trajectory at approximate 1 cm intervals (**Fig. 2**).
4. Once the radiologist deemed the needle to be at the margin of the fluid collection, the participant was instructed to advance the needle into the collection.

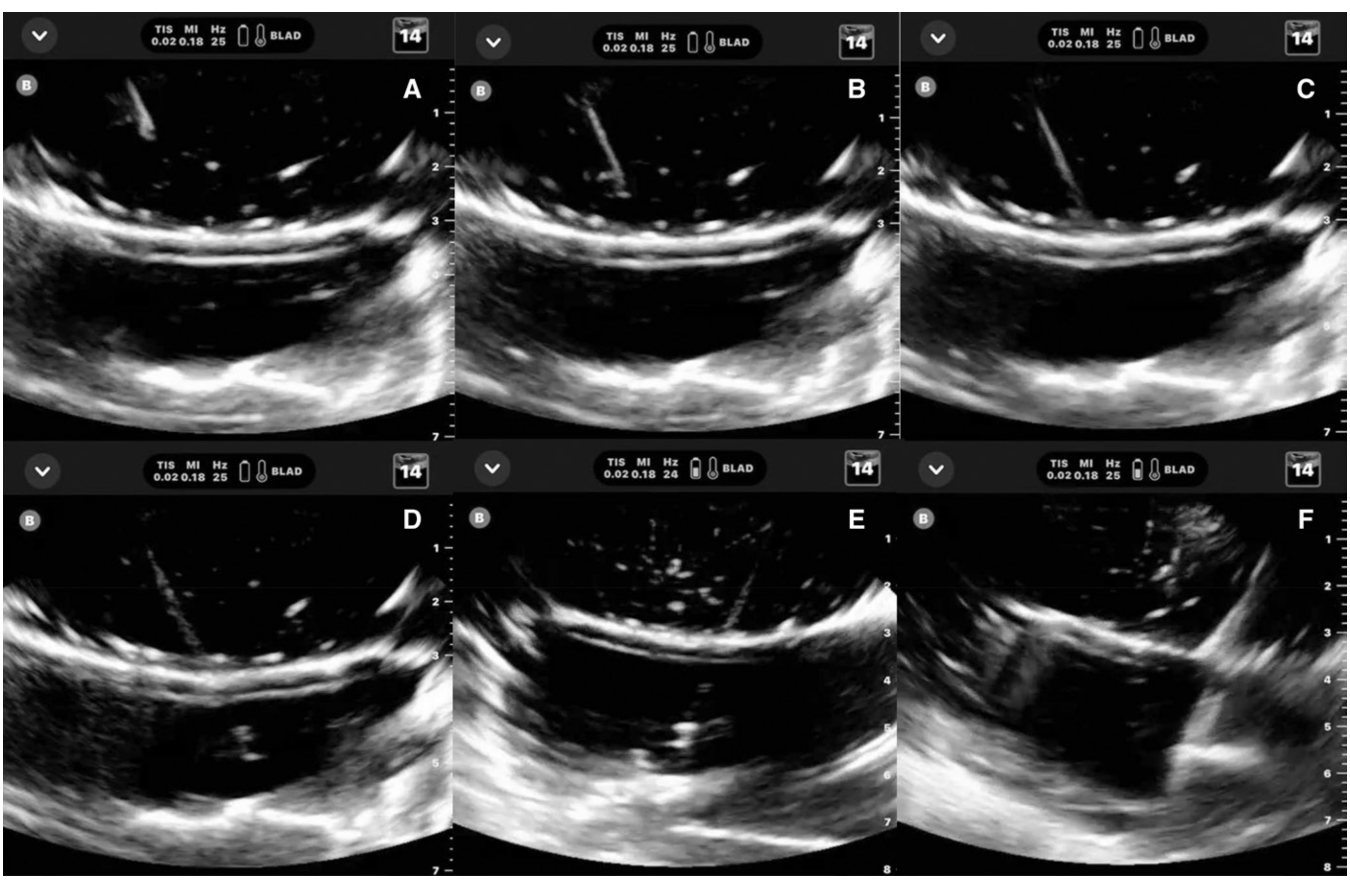

Fig. 2. Ultrasound images showing: A–D) advancement in a stepwise fashion of the introducer needle with the needle traversing A–B) simulated soft tissue, C) at the soft tissue/abscess interface, and D) with tip within the simulated abscess. In a different attempt, the 0.035″ guidewire is visualized E) within the abscess through the introducer needle with F) the final position of the drain coiled within the abscess.

5. Once the radiologist confirmed the needle tip was at least 1 cm into the collection, the participant was instructed to remove the inner stylet of the introducer needle while keeping the needle in place.
6. The participant was instructed to confirm needle tip location within the fluid collection by applying pressure to the collection, resulting in expression of fluid through the needle.
7. The participant was instructed to then advance a 0.035" or 0.038" Lunderquist or Amplatz wire through the needle into the fluid collection.
8. Once initial resistance was felt by the participant, the participant was instructed to continue advancement of the wire to form a coil within the collection.
9. The participant was instructed to remove the access needle while keeping the wire in place using a "pinch pull" technique (pushing and pinching the wire in place while pulling the needle in retrograde fashion from the wire).
10. Once the needle was removed from the wire, the participant was instructed to place the prepared drain onto the wire and advance the drain to the surface of the phantom.
11. The participant was then instructed to advance the drain over the wire into the fluid collection using a "pinch and push" technique (pinching the wire to keep it in place while slowly advancing the drain forward through the simulated tissues).
12. When resistance was felt by the participant, the participant was instructed to use ultrasound to visualize the drain tip within the collection. The positioning was confirmed by examination of the images by the radiologist.
13. The participant was then instructed to remove the inner stylet/stiffener and wire in retrograde fashion while advancing the drain to form the coil within the fluid collection.

Technical success was defined as placing the catheter coiled tip within the fluid collection. Confirmation of technical success was assessed by applying pressure to the phantom resulting in expression of fluid and/or aspiration of fluid with a syringe via the drain. The number of needle redirections and the time to perform the procedure were also recorded for each participant. The mean and standard deviation for each variable were calculated for both groups and compared using an unequal variance (Welch's) *t*-test.

RESULTS

There were 31 interventional radiology-naïve participants recruited. One was urgently summoned to hospital duties during the procedure and the attempt was aborted. In another attempt, the phantom experienced a mechanical failure. Of the remaining participants, all 29 demonstrated technical success (**Table II**). Of these, 26 successfully placed the catheter without the need to redirect the trocar needle, while three required a single needle redirection. No participants required more than one redirection. The time to perform the procedure ranged from 4 to 11 min, with a mean time of 5.8 min. Four attending radiologists and physician associates (PA) at a major academic hospital with experience performing ultrasound guided procedures also completed the simulation. All four subjects demonstrated technical success with one participant requiring one redirection. All four control subjects required 2 min for completion.

Table II. Rates of Success, Time to Completion, and Number of Redirections for Test and Control Groups.

GROUP	MEAN	SD	RANGE	UNEQUAL VARIANCES *t*-TEST *P*-VALUE
Test Group [Technical Success: 100% (29/29)]				
Minutes to Completion	5.8	±1.4	4 to 11	
Redirections	0.1	±0.4	0 to 1	
Control Group [Technical Success: 100% (4/4)]				
Minutes to Completion	2	±0	2 to 2	<0.001
Redirections	0.25	±0.5	0 to 1	0.69

DISCUSSION

Treatment goals for surgical intervention in the space environment involve maximizing the ability to treat a variety of pathologies while minimizing equipment mass and volume, procedural complexity, and complication rate.[2] Ultrasound-guided percutaneous drain placement can be used to symptomatically palliate or curatively treat a multitude of potential surgical emergencies which may be encountered during spaceflight, particularly exploration class missions for which medical evacuation is not possible.[5,7,9] Conditions specifically included on the NASA Exploration Medical Capabilities list whose potential sequelae may be amenable to this intervention include abdominal injury, appendicitis, nephrolithiasis, urinary retention with stricture, acute cholecystitis, acute pancreatitis, and acute diverticulitis.[15] This list was formulated based on conditions with a potential to occur in spaceflight based on analog populations and historical spaceflight incidence data. Ultrasound-guided percutaneous drain placement is also relatively low risk, quickly learned, and can be performed with minimal equipment.[11] This limited equipment requirement minimizes the mass and volume penalty with far less than a kilogram required for the entire system if excluding the mass of the ultrasound probe.[9] There is no need for general anesthesia or moderate sedation, and there is potential for rapid recovery of the crewmember to near full function. Furthermore, it can be performed in a stepwise process, allowing for guidance by a remote terrestrial guide and/or audiovisual teaching tool.

As current missions do not extend beyond low Earth orbit and medical evacuation to high level of terrestrial care is available within 24 h, the need for such guided interventions has not yet been urgent. However, planned lunar and Martian missions lasting months to years, including future Artemis missions, extend beyond the safety net of emergent evacuation and treatment. Surgical emergencies would require immediate largely autonomous treatment capabilities. There are at present no fellowship-trained interventional radiologists or other similar imaging-guided proceduralists in the NASA Astronaut Corps. However, there are personnel with backgrounds in emergency medicine, general surgery, and internal medicine, among others, who may be able to quickly master basic imaging-guided procedural skills. Given the high rate of technical success, the technique presented in this paper may be effective to allow for just-in-time training of these highly educated personnel when and where live guidance is available.

Multiple study limitations were present, some of which were unavoidable, including but not limited to the small size of the control group, lack of microgravity, no significant differences in tissue densities between gel and fluid on ultrasound, and only minimal delay in video communication. Additionally, the simulated "patient" in this case does not fully mirror the challenges of drain placement on a live subject, particularly one who is acutely ill and potentially physically incapacitated. Of particular concern are difficulties of patient immobilization, administration of local anesthetic, and control of the small volume of bodily fluids (blood, pus, urine, etc.) likely to be generated during catheter insertion. None of these challenges could be evaluated well with our experimental setup but will complicate the procedure in spaceflight.

However, this proof-of-concept work does demonstrate that this sample of educated but minimally to nonprocedurally trained individuals could consistently successfully complete the steps required for percutaneous drainage when provided with a brief instructional video and live guidance. Despite the small sample size, the procedurally naïve participants required a statistically significantly longer period of time to complete the procedure compared to the experienced physicians and physician assistants, but there was no statistically significant difference in needle redirections. This work also supports the proposition that just-in-time training with two-way live audiovisual support from a remote expert may represent a feasible pathway for avoiding dedicated extensive preflight training in these minimally-invasive surgical interventions. This capability to successfully teach then guide such procedures remotely, however, could also be applied to terrestrial environments, such as polar research stations, submarines, and resource-limited regions of the developing world. While the minimal communications delay present in our setup might simulate well the near future potential low Earth orbit, cis-lunar, and some near-Earth asteroid intercept missions, exploration class Mars missions with longer delays will require further study, as two-way communication times will extend up to 40 min.[10] In addition to testing longer communication delays utilizing this method of instruction and stepwise guidance, further work should explore its implementation in more closely related analogs to microgravity, such as parabolic or suborbital flight.

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Swan Song

By Pamela C. Day

Over the past 42 years the job of Managing Editor of our Blue Journal has evolved quite a bit. When I started working for the Aerospace Medical Association in 1980, my job as editorial assistant was to copy manuscripts and mail them to the typesetter and proofread the proofs when they came back to the office. I was also responsible for billing, advertising, and keeping track of ad placement in the journal. The upkeep of member files was also in my purview. I was hired to assist our Managing Editor, Fred Stoffel, who was first and foremost a journalist and news photographer who happened to end up at AsMA, much like I did. My background as an artist occasionally came in handy, but it was my trainability and my degree from a college in his hometown of Appleton, WI, that convinced Fred to take a chance on me.

When Fred retired in 1990, I thought I was ready to handle this job! Sometimes I was, sometimes I wasn't. I have worked with three Executive Directors and six Editors-in-Chief. I have had seven assistants to help me along the way. One lasted only about a week, most stayed a couple years before moving on. We were lucky to hire Rachel Trigg, who has been with us since 2003, and is now poised to take over as Managing Editor!

Now as I prepare to leave AsMA, I can look back on how the job has changed. First, we got computerized and sent our edited manuscripts on discs instead of xeroxed copies. And now we upload them to an ftp site. We used to publish a membership directory every year (I proofread the whole thing, which is how I remember the middle initials of older members!). Now we have a website with a search engine to help members locate each other. We used to publish a news section at the back of the journal with pages devoted to our constituent organizations. Now Rachel has created an online newsletter published monthly with the most up-to-date information.

The scientific program used to be something the journal published, but we had no role in its makeup. Now much of my time is spent managing the online system for abstract submission and working throughout the year on the Scientific Meeting Program. That is another process that has evolved from sending abstracts typed in a blue box so we could cut and paste them for publishing to the online portal we now use. Over the years I have used at least five different abstract management systems.

The job now entails such things as photographing the highlights of the annual scientific meetings; managing the abstract submission system; publishing the meeting program and addendum; the honors night awards biographies, press releases, and brochure; coordinating with all vendors for typesetting, printing, mailing, advertising; editing manuscripts and proofreading; coordinating all association publications, brochures, and advertising; creating and enforcing style in coordination with scientific notation and style; managing licensing agreements for subscriptions; pricing of subscriptions and pdfs and open access, etc., etc., etc. It really is a 'Jack of all trades' kind of job. This job isn't for everybody . . . and not just anybody would want it! Lucky for us, Rachel does!

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DECEMBER 1997

Sleep and aviation (National University Hospital, Copenhagen, Denmark): "Aviation safety reports indicate that many incidents are related to fatigue. Obstructive sleep apnea (OSA) is characterized by irregular snoring with repeated apnea episodes during sleep and excessive daytime sleepiness. Deprived of sleep, patients suffer from daytime sleepiness and involuntary sleep attacks. The prevalence of OSA among adult men is more than one percent, 0.5% in women. Predisposed are men aged 40-65 yr. Many patients, including pilots, are unaware of their sleeping disturbance and the symptoms are not easily recognized. Therefore, this condition may not be discovered during a regular health examination. However, this condition can be effectively treated. In our opinion, pilots suffering from OSA do not necessarily have to lose their certificate. Diagnosis and treatment can be conducted, followed by regular checkups. We suggest that questions about sleep be included in pilots' health examinations."[3]

DECEMBER 1972

Altitude decompression sickness (Air Force Inspection and Safety Center, Norton AFB, CA): "Some United States Air Force operations require crew members to fly at high altitudes protected by pressurized cabins, oxygen equipment or pressurizing garments – either singly or in combinations. Evolved gas decompression sickness can occur when the primary protective equipment or systems fail or are inadequate to protect the individual.

"Cases of decompression sickness occurring in flying operations and reported to the Life Sciences Division on Air Force Form 711gA were analyzed to determine causative factors and severity. As might be expected, the primary cause was inadequate aircraft pressurization coupled with inadequate crew denitrogenation. Most cases were bends-type decompression sickness, although six cases had central nervous system involvement. Of these six cases two required treatment in a hyperbaric chamber…

"Flight surgeons should be alert to detect those cases which will require hyperbaric therapy and be familiar with procedures necessary to obtain such therapy."[2]

DECEMBER 1947

Psychology and safety of flight (American Institute for Research, Pittsburgh, PA): "[P]reliminary studies have shown that many of the psychological requirements found essential for effective work as a military pilot are also important for the airline pilot. It is also clear, however, that many of the requirements are different. It is strongly recommended that a coordinated large scale attack be made on the problem of determining the requirements for achieving maximum safety in flight. The possible errors of pilots must be known, especially to the pilots. Pilots must be assisted in obtaining all types of information and skills necessary for safe flight. Only those who have the essential aptitude and temperament requirements should be allowed to begin a career as an airline pilot."[1]

Fig. 1. "Subject in correct position preparatory to reaching for firing curtain. Accelerometers can be seen on the hip, shoulder, and head."

Ejection tolerance (Aero Medical Equipment Laboratory, Naval Air Experimental Station, Philadelphia, PA): "Results are given of sixty ejection seat experiments in which volunteer subjects were exposed to maximum acceleration in the range of approximately 18 to. 21 g [**Fig. 1**]. It is concluded that, under the conditions of the experiments, average men can tolerate this acceleration, which is adequate to eject aviators from aircraft."[4]

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This column is prepared each month by Walter Dalitsch III, M.D., M.P.H. Most of the articles mentioned here were printed over the years in the official journal of the Aerospace Medical Association. These and other articles are available for download from Mira LibrarySmart via https://submissions.miracd.com/asmaarchive/Login.aspx.

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Meet the New Managing Editor: Rachel Trigg

With the retirement of Pamela Day as Managing Editor after nearly 43 years, Rachel Trigg will assume those responsibilities beginning in 2023. Rachel has been with AsMA for 20 years, working her way up from Editorial Assistant back in 2003 to Managing Editor.

A native of New York, Rachel earned a B.A. from Friends World College in Lloyd Harbor, NY. During that time, she traveled to the United Kingdom, where she spent 2 years as part of the program to earn her degree and wrote a thesis on folk tales and folk songs. While there, she also volunteered with a home for retired veterans, where she learned a lot of local history which became part of her thesis. Additionally, she volunteered with an environmental group who took weekend excursions to national parks to clean up and restore trails. After returning to New York, she spent a year studying Library Science, but due to cutbacks, the program was cancelled. She then worked as a temporary writer/editor for the Federal Emergency Management Agency (FEMA) after the no-name nor'easter in 1992 that destroyed hundreds of homes on eastern Long Island, snapped underwater cables, and created a new inlet. She was kept on for the first World Trade Center bombing in 1993 when the same FEMA crew moved to New York City.

Rachel went on to earn a certificate as a Publications Specialist at George Washington University. She was a freelancer for the Alexandria Gazette-Packet for 5 years, writing restaurant and theater reviews along with producing the weekly calendar, proofreading, and doing layout, before becoming a Proofreading Supervisor at Direct Press Modern Lithograph. She became an Editorial Assistant at the Aerospace Medical Association's (AsMA's) journal in 2003, editing and proofreading articles for the journal. She worked her way up to Assistant to the Managing Editor and then Assistant Managing Editor. Along the way, she took on further duties such as editing AsMA's website, producing the monthly newsletter, and assisting with subscriptions.

Rachel was a volunteer coordinator at a local church in Alexandria for years and also helped another group put together meals to serve to the unhoused in Washington, DC. She enjoys embroidery, knitting, and crocheting. She is also interested in cooking and graduated from Stratford University with a diploma in the culinary arts. She enjoys cooking videos and has a large collection of cookbooks, including regional church collections, international cuisines, and historical recipes.

Bates is 2022-2024 IAMFSP President

Col. Christopher W. Bates, B.S., M.D., is the 2022–2024 President of the International Association of Military Flight Surgeon Pilots (IAMFSP). He is currently the sole tanker Pilot-Physician for the USAF and is actively engaged in human system integration issues for the KC-46. As a KC-46 instructor-pilot he works with 22d Operations Group in the execution of KC-46 Initial Operational Test and Evaluation and training of KC-46 aircrew. Prior to this assignment Col. Bates was the Commander of the 22d Operational Medical Readiness Squadron, 22nd Medical Group, 22nd Air Refueling Wing, McConnell AFB, KS.

Col. Bates was commissioned through the U.S. Air Force Academy in 2001 and earned his Doctor of Medicine in 2005 from Uniformed Services University of the Health Sciences (USUHS). He then served an Internal Medicine internship at San Antonio Uniformed Services Health Education Consortium (SAUSHEC), San Antonio, TX, in 2006 and graduated from the Aerospace Medicine Primary Course at Brooks City-Base. He served an Emergency Medicine residency at SAUSHEC in 2011 and graduated from undergraduate pilot training at Vance AFB, Vance, OK, in 2015. He attended Air War College at Maxwell AFB, AL, by correspondence in 2021.

Col. Bates is a Pilot-Physician with over 2000 pilot flight hours in the T-6, T-1, KC-135, and KC-46. He has deployed as a pilot, flight surgeon, and critical care air transport team (CCATT) physician in support of Operation Enduring Freedom and Operation Iraqi Freedom He is also a board certified emergency medicine physician and a Fellow of the American College of Emergency Physicians.

1st International Conference in Aerospace Medicine (ICAM), Paris, France

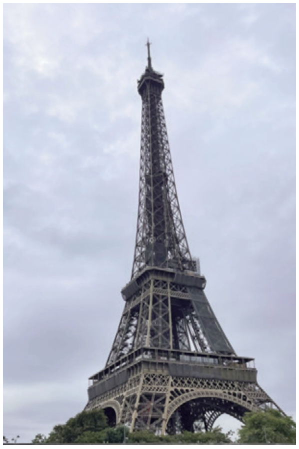
The 1st International Conference in Aerospace Medicine (ICAM) was held September 22 – 24, 2022 at the City of Science and Industry in Paris, France. This was the first scientific meeting organized by four of the largest Aerospace Medicine organizations in the world: the International Academy of Aviation and Space Medicine (IAASM), the European Society of Aerospace Medicine (ESAM), the Societé Francophone de Médicine Aéronautique et Spatiale (SOFRAMAS), and the Aerospace Medical Association (AsMA). This collaboration began organizing the ICAM in 2019 and the conference was originally scheduled for September 2020 in Paris, France. However, the COVID-19 pandemic required the conference to be delayed to September 2021. The ICAM Organizing Committee, led by Dr. Vincent Feuillie and Dr. Brigitte Guidez of SOFRAMS, continued to meet and develop a scientific program but realized in early 2021 that the COVID-19 pandemic would not allow for adequate international travel in September 2021 so the ICAM was again postponed to September 2022.

Aerospace Medicine professionals from around the world traveled to Paris, France in September 2022 to participate in the 1st ICAM. A total of 845 registrants from 78 countries! A truly international audience.

A strong scientific program was developed by Dr. Olivier Manen of SOFRAMAS and Dr. John Crowley of the IAASM. The 2022 IAASM

City of Science and Industry, Paris, France. (https://www.tourby-transit.com/paris/things-to-do/cite-des-sciences-et-de-iindustrie-la-villete).

Cercle National des Armées, Paris, France (from https//structurae.net/en/structures/cercle-national-des-armees).



The Eiffel Tower, Paris, France. Photo by Jeff Sventek.

Andre Allard Lecture kicked off the ICAM scientific program. Mr. Luc Tytgat, the Director of the Strategy and Safety Management Directorate for the European Union Aviation Safety Agency spoke about aviation safety. The Andre Allard Lecture was followed by the 2022 John Ernsting Panel. This panel was also sponsored by the IAASM and was co-chaired by AsMA President, Dr. Susan Northrup, and the International Airline Medical Association (IAMA) President, Dr. Elizabeth Wilkinson. The panel was dedicated to "COVID-19 Aerospace Medicine Risk Mitigation, Controversies and Lessons Learned." Following these plenary sessions, three scientific sessions were offered in parallel. Participants were encouraged to attend the session that offered scientific presentations that most interested them. This pattern of plenary sessions and parallel scientific sessions was followed on each of the three meeting days.

Accompanying Persons were offered several sight-seeing opportunities during the ICAM. Paris has so much to offer everyone and the sight-seeing opportunities offered by SOFRAMAS were in parts of Paris not normally considered by tourists. Special thanks to Dr. Patricia Maruani of SOFRAMS for organizing the Accompanying Persons sight-seeing program. Accompanying Persons were offered tours of:

- Musée des Arts Forains (Fairground Museum)
- Musée Marmottan Monet (Marmottan Monet Museum)
- Musée du Parfum-Fragonard (Fragonard Museum of Perfume)
- Musée Carnavalet (Carnavalet History of Paris Museum)

Social events were also a big success during the ICAM 2022. A wonderful Welcome Reception was offered to all registrants and accompanying persons on the evening of Thursday, September 22. This event was held at the City of Science and Industry and offered all in attendance the opportunity to reconnect with old friends and make new friends. Academicians of the IAASM were offered the opportunity to participate in the Academician's Dinner on Friday evening, September 23. The Academician's Dinner was held at the Cercle National des Armées in Paris. The Cercle National des Armées is housed in a palace of neo-classical inspiration completed in 1927 on the plans of the architect of national monuments Charles Lemaresquie and built on the site of part of the Pépinière barracks. The House of Officers of the Cercle National des Armées welcomes active, retired or reserve officers, civil servants of category A or assimilated from the Ministry of the Armed Forces , as well as holders of the Legion of Honor, auditors and former auditors from the Institute for Advanced National Defense Studies or the Center for Advanced Armament Studies, as well as their families and guests. This building was dedicated in 1954 to the memory of Marshal Joffre. Finally, the ICAM Gala Dinner was attended by a large number of registrants and accompanying persons on Saturday evening, September 24. The Gala Dinner was held in the City of Science and Industry and allowed the attendees one last opportunity to socialize at the end of the ICAM.

Paris was the perfect city to host this 1st ICAM with its rich aviation history, beautiful architecture, and rich culture. Many thanks go to our SOFRAMAS colleagues for organizing the ICAM and making it so enjoyable for all in attendance. Plans for a 2nd ICAM are underway and information will be made available as soon as those plans firm up. We hope to see many of you at the next ICAM.

Hudson Receives Kidera Award

Martin Hudson, M.B.B.S., MRCP (UK), FRCP Edin., was presented with the George J. Kidera Award from the International Airline Medical Association (IAMA) at the International Conference on Aerospace Medicine (ICAM) in Paris in September. The award is given annually in recognition of outstanding achievement in the field of Aviation Medicine.

Dr. Hudson served his residency at St. Bartholomew's Hospital, London, in 1965. After obtaining a Private Pilot's License, he joined the Medical Branch of the Royal Air Force and became a member of the Royal College of Physicians in 1971. From 1972 to 1999 he was in General Practice and in 1977 became a UK CAA Authorized Aviation Medical Examiner. He was awarded the Fellowship of the Royal College of Physicians of Edinburgh in 1998 in recognition of his research and teaching in the field of hypertension.

KIDERA AWARD—Dr. Martin Hudson, recipient of the 2022 IAMA George J. Kidera Award, which was presented to him at ICAM 22 by Dr. Elizabeth Wilkinson, President of IAMA, and Dr. Brinio Veldhuijzen van Zanten from the IAMA Awards committee.

In 1999, he set up an Aviation Medicine Consultancy as an approved Aviation Medical Examiner for the European Aviation Safety Agency (EASA), UK Civil Aviation Authority (UK CAA), USA Federal Aviation Administration (FAA), Transport Canada (TC) and the Civil Aviation Safety Authority of Australia (CASA). He was appointed as the Consultant Aviation Medicine Adviser to Thomas Cook Airlines (UK) in 2000 and continued in this role until October 2017.

Dr. Hudson was a Vice-President of the UK Association of Aviation Medical Examiners, having served for 12 years as its Treasurer and then for 3 years as Chairman. He has been a member of the Aerospace Medical Association (AsMA) since 2000 and was appointed a Fellow of the AsMA in 2013. He served as Chairman of AsMA's Air Transport Medicine Committee for 4 years from 2011 to 2015 and was a member of the AsMA Mental Health Group. He served as President of the Airline Medical Director's Association from 2018–2019. He was also a member of the European Society of Aerospace Medicine (ESAM) Advisory Board and served as the ESAM liaison representative with ICAO. In 2017 he co-authored a chapter in Professor Robert Bor's latest book on 'Pilot Mental Health'. He was also much involved with the development of Peer Support Groups both for Airline Pilots and for Aviation Medical Examiners.

Dr. Hudson recently retired after over 40 years as an AME, announcing this during the Kidera award ceremony: "To have my name added to the previous winners of this award is very humbling, but there could not have been a better way to finish my 45-year career in Aviation Medicine. This has been immensely rewarding and I am pleased to think that I have made a contribution to this amazing and important scientific discipline. In this I have had enormous and dedicated support from my wife Sue, who has also enjoyed the journey with me. This would not have been possible without her."

NOMINATE A COLLEAGUE FOR AN AsMA AWARD!

The deadline is January 15!

The Award Submission Site is open for nominations. Log in to the Members Only section of the AsMA website: www.asma.org. On the left menu you will find a link to the online award nominations system.

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Thank you to the reviewers of *Aerospace Medicine and Human Performance*. The high quality of our peer review is dependent upon the contributions of these volunteers. This list covers the period of November 1, 2021, through October 2022.

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Aerospace Medicine and Human Performance

December 2022

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