INFORMATION PAPER ON THE IMPACT OF EXPOSURE TO HIGH GRAVITATIONAL FORCES

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RELEVANCE TO THE DEPARTMENT OF DEFENSE

As discussed in detail below, military pilots of high-maneuverable fighter aircraft are often exposed to sudden changes in G-force during training and combat, which can result in periods of loss of consciousness or other neurocognitive symptoms that may impact mission and personnel safety. The threshold for G-forces above which aircraft pilots experience adverse neurologic consequences, including LOC, is well-documented. Known protective measures are standard components of G-force awareness training required for all military aviators and pilots that operate high performance aircraft. However, the cumulative effects of multiple high G-force exposures on brain health and behavior have not yet been adequately investigated.

KEY POINTS & IMPACT TO THE WARFIGHTER

- Military pilots and crew of high-performance aircraft throughout the services are regularly exposed to high G-forces, which can cause transient conditions like an altered state of awareness and gravity induced LOC, or G-LOC; G-LOC specifically occurs upon exposure to forces at 9 G or above.
    - These effects are largely due to rapid physiologic shifts that occur within seconds of exposure, which are primarily related to a decrease in blood flow to the brain and decreased brain oxygen saturation.
- Evidence regarding the association of factors like height, weight, BMI, and exercise training with G-LOC incidence and G-force tolerance is inconclusive due to the limited number of studies in this area, as well as the conflicting findings among available studies.
- Many studies demonstrate the benefits of using G-suits, performing the anti-G-force straining maneuver, and undergoing human centrifuge training, each of which are standard components of G-force risk management strategies in the U.S. Air Force.
    - These measures are thought to improve tolerance by promoting cardiovascular adaptation to G-force exposure and preventing blood from pooling in the legs and feet that contributes to G-LOC.
- While the long-term cognitive and behavioral effects of multiple high G-force exposures are unclear, some studies indicate that senior military pilots exhibit

functional and cognitive changes in the brain consistent with adaptation to the cognitive challenges of frequent flight.

- Additional well-designed prospective studies are needed to evaluate the long-term cognitive and behavioral effects of multiple high G-force exposures among military pilots.

PURPOSE

This information paper reviews available evidence on the neurological impact of single and multiple high G-force exposures in pilots of high-performance aircraft.

BACKGROUND

Military pilots of high-performance aircraft have long reported serious physiologic responses, including hypoxia (decreased oxygen availability in body tissues); heat stress; dehydration; disruptions in circadian rhythm; and gravity-induced LOC, or G-LOC.[1] While advancements in the design of modern high-performance aircraft have improved pilot survivability during agile maneuvers, reports of G-LOC have been noted since 1929[2] with an estimated 9-20% of military pilots impacted.[3-5] Pilots are exposed to high gravitational forces along six different axes. The force along the head-to-toe axis is the primary safety concern and is commonly referred to as G-force.[6] One G is defined as the acceleration of an object due to the force of gravity on Earth, which is 9.806 meters per second squared. Military pilots of high-performance aircraft also report a variety of other behavioral, cognitive, and sensory symptoms, including poor response to auditory stimuli, memory difficulties, motor symptoms, euphoria, apathy, depersonalization, confusion, and a dreamlike state that occur with rapid onset following high G-force exposure and do not involve LOC.[7] Brief periods of confusion and cognitive impairment in military pilots of high-performance aircraft, presumably associated with exposure to high G-forces, were first reported in the 1980s.[8,9]

G-LOC likely occurs at or above 9 G because acceleration at that rate forces blood from the head to the feet, resulting in reduced blood flow to the brain and cerebral hypoxia or anoxia (defined as a complete lack of oxygen supply to the brain).[9] The average human cerebral anoxic reserve time is 6-7 seconds at 9 G, meaning that a pilot has only 4-5 seconds to reduce acceleration before G-LOC occurs.[10] Additionally, aircrew exposed to G-forces that are insufficient to cause G-LOC (6-8 G) can exhibit a transient altered state of awareness termed almost LOC, or A-LOC, which involves a wide variety of cognitive, physical, emotional, and physiological symptoms.[8] One survey study of 65 active duty fighter pilots noted that nearly all had experienced at least one visual or cognitive disturbance in the high G-force environment, including grayout in 98%; blackout in 29%; A-LOC symptoms (such as abnormal sensation in limbs, disorientation, and confusion) in 52%; and G-LOC in 9%.[5] Given these statistics, it is important to learn why these problems happen to mitigate them and maintain force readiness. Some research studies have also begun to evaluate the effects of cumulative high G-force exposures with the aim of understanding and addressing health outcomes throughout a pilot's military service.

ACUTE PHYSIOLOGICAL RESPONSE TO HIGH G-FORCE EXPOSURE

Autonomic Responses

The autonomic nervous system's physiologic response to G-forces plays an important role in predicting the adverse effects of such exposures. While most studies report no clinically significant cardiac arrhythmias with high G-force exposure,[11-13] increases in heart rate have been reported in multiple studies.[14] This increase in heart rate occurs because there is typically a decrease in blood pressure and blood pooling in the lower extremities upon exposure to high G-forces. The autonomic nervous system compensates by increasing heart rate through a response known as the baroreceptor reflex, which helps regulate blood pressure.[6] How quickly the heart rate changes in response to high G-force exposure depends on several factors, including the level of G-force and the G-force tolerance of the human body, defined as the ability to withstand exposure to high G-forces.[15,16]

Reduced Cerebral Oxygenation

Due to the reduced blood flow to the brain that occurs with exposure to high G-forces, the supply of oxygen to the brain also decreases, which can considerably impair neurocognitive function. The decrease in brain oxygenation that occurs with exposure to as low as 3-4 G can impair the ability to discriminate between visual stimuli,[17] while higher G-force levels may result in other impairments like slowed reaction time.[18] Brain oxygen saturation can be measured noninvasively using a technique known as near-infrared spectroscopy, or NIRS. This method uses the absorption of light at near-infrared wavelengths to measure changes in the oxygen saturation of specific molecules like hemoglobin to infer oxygen saturation within a tissue.[19] One study used NIRS to investigate the relationship between brain oxygen saturation and the incidence of G-LOC or A-LOC, G-force level, duration of G-force exposure, and incapacitation time after G-LOC.[19] The results showed that once brain oxygen saturation decreased to a certain level, G-LOC occurred regardless of the G-force level or the duration of exposure. Additionally, the longer brain oxygen saturation remained below this threshold, the longer the individual remained unconscious after G-LOC.[19]

Some have proposed that conditions like A-LOC and G-LOC occur because when the brain does not receive enough oxygen, it shuts down higher-order cognitive functions to prioritize sustaining life.[20] This hypothesis was supported in one study, which used data on oxygen saturation changes in specific brain regions following high G-force exposure to develop a computational model.[21] The model accurately predicted performance on specific cognitive tasks using this information.[21] In another study, nine volunteers from the Naval Air Warfare Center Aircraft Division were exposed to short 6, 8, and 10 G-force pulses of increasing duration until they experienced G-LOC while being monitored with NIRS.[8] The participants exhibited a number of physical, cognitive, and emotional symptoms consistent with A-LOC, including eye movements, confusion, amnesia, and difficulty forming words. Additionally, the study observed that these symptoms began when brain oxygen saturation decreased, and there was a faster change in brain oxygen saturation after G-force exposures that caused A-LOC than after asymptomatic G-force exposures.[8]

Electrophysiological Changes

In addition to changes in autonomic function and cerebral oxygenation, changes in brain activity following high G-force exposure have been observed in studies using EEG. In one study, 16 healthy male participants were subjected to two different hypergravity protocols: a continuous 2 G environment for 30 minutes; and 5 repeated 3-minute intervals of 2 G followed by rest.[22] The results showed that the continuous 2 G exposure altered EEG activity in two specific brain regions and produced feelings of decreased motivation, while the intermittent exposure resulted in no EEG or mood changes.[22] A centrifuge study of 10 individuals exposed to high G-forces resulting in G-LOC observed that 2 unique EEG waveforms appeared just prior to G-LOC and just prior to the return of consciousness and were associated with regional changes in brain oxygen supply measured by NIRS.[23] Participants performed tracking and mathematical tasks before and after G-LOC. When consciousness returned, the supply of oxygen to the brain was restored within approximately 15 seconds, but it took approximately 60 seconds for EEG and performance to recover. This finding suggests that after G-LOC, it takes more than a return to normal oxygen levels to recover cognitive function.[23] This hypothesis is supported by the abovementioned study on A-LOC, during which A-LOC symptoms continued well after brain oxygen saturation recovered.[8]

Vestibular Effects

Some studies have reported transient vestibular effects of high G-force exposure, though the duration and level of exposure appear to be contributing factors. One centrifuge study reported vestibular symptoms in 5 healthy participants subjected to a 5-minute 3 G exposure,[24] while another found no significant change in vestibular function after a 9 G exposure among 11 pilots.[25] Additional studies are needed to more precisely determine the vestibular effects of different G-force exposures.

Neuropathological Changes

In rodent studies, exposure to high G-forces resulted in increased injury biomarkers such as heat shock protein, and neuronal damage in various areas of the brain.[26,27] While the release of heat shock protein is most pronounced with very high G-force exposure (greater than 10 G), it has also been observed with repeated exposure to subthreshold G-forces (less than 4 G).[26] One preclinical study also found that both hypergravity and simulated weightlessness can kill neurons and impair learning and memory.[28]

In summary, the physiologic impact of rapid acceleration is well described in studies of pilots of high-performance aircraft. The most consequential effect is the pooling of blood in the lower extremities, which can cause cerebral hypoxia or anoxia. If the exposure is extreme (greater than 9 G) or prolonged (greater than 6-7 seconds), LOC is likely. Additionally, evidence suggests changes in cognitive function with high G-force exposure may involve reduced neuronal activity in specific brain regions in response to reduced blood flow and oxygen. While there is some preclinical evidence that frequent exposure to high G-forces may injure neurons, more human studies evaluating the neuropathological impact of multiple high G-force exposures are needed to confirm these findings.

FACTORS ASSOCIATED WITH G-FORCE TOLERANCE

Some studies have aimed to identify the specific factors related to G-force tolerance and the risk of G-LOC or other adverse effects of high G-force exposure. One such factor is the difference in cardiovascular response to high G-force exposure. A retrospective study of data collected from 873 Taiwanese Air Force trainee pilots over a 9-year period examined this relationship in pilots who were undergoing human centrifuge training,[6] which is commonly used to assess the G-force tolerance of fighter pilots. In this study, the training protocol involved a progressive increase in exposure levels from 0-7.5 G. Those who passed the training (defined as those who could sustain the 7.5 G exposure for 15 seconds) had significantly lower resting heart rates at baseline and just before exposure to 7.5 G. Additionally, those who passed showed a significantly greater increase in heart rate during the first 1-5 seconds of exposure to 7.5 G.[6] This finding of a greater increase in heart rate early during high G-force exposure was also reported in a separate study comparing military pilots who passed 9 G centrifuge training with those who did not.[29] Together, these findings suggest that those with higher G-force tolerance may have stronger baroreceptor reflex activity and may be less susceptible to G-LOC.[6]

Evidence is inconclusive on the extent to which factors like weight, body mass index, and height affect G-force tolerance. The Taiwanese study showed that those who passed the 7.5 G training had a significantly higher BMI and weight than those who failed, but there were no significant differences in height or age.[6] Similarly, one study reported significantly higher BMI in individuals who passed 9 G centrifuge training than in those who did not.[29] Another study investigating aviators of U.S. Navy aircraft also reported there was no association of G-LOC incidence with pilot age or height, but unlike the prior studies, this study also found no association with weight.[30] Other studies have similarly reported no significant relationship between weight or height and G-force tolerance.[31-33]

Evidence regarding the relationship between specific exercise programs and G-force tolerance is also inconsistent, but most studies report no association. Three small studies (less than 25 participants) found significant associations between strength training and G-force tolerance,[34-36] with one of these studies reporting a 53% increase in G-force tolerance among individuals who completed a weight training program.[35] However, this finding has not been replicated in larger studies. One study reported that factors including the type of exercise a pilot performed (aerobic exercise versus weight training), missed meals, and heat exposure were not associated with G-LOC incidence.[37] Similarly, other studies have reported no association of physical fitness or different exercise training programs with G-force tolerance[38,39] or G-LOC incidence.[40] One of these studies, on 361 Korean Air Force pilots under age 40, reported that specific physical characteristics like muscle mass, strength, and endurance did not significantly differ between those who experienced G-LOC during centrifuge training and those who did not.[40]

Some evidence suggests that the impact of G-force load may not be homogenous and could depend on the specific outcomes that are evaluated. In one study, a group of 10 pilot cadets subjected to accelerations in a centrifuge were compared with control pilots not subjected to G-forces; the results showed that attention switching was better in the group exposed to G-forces, but visuospatial working memory was worse.[41] However, a key limitation of the study is that the level of G-forces in the exposed group was not specified, making it difficult to come to accurate conclusions on how G-force exposure may impact specific cognitive functions. Collectively, these data indicate that additional research is warranted to determine the environmental and physiological factors related to the adverse effects of high G-force exposure.

PROTECTIVE MEASURES

The main strategies to prevent G-LOC and help the fighter pilot sustain consciousness when exposed to high G-force include wearing a pressurized anti-G-force garment or G-suit, performing the anti-G-force straining maneuver or AGSM, and centrifuge training.[37,42-45]

G-Suits

G-suits are whole-body garments designed to inflate in high G-forces to help prevent the shift of blood away from the brain, thereby helping to prevent G-LOC.[46,47] Early studies on G-suits aimed to evaluate efficacy, safety, and design and implementation features that could improve their ability to prevent G-LOC.[46] An early study confirmed that G-suits increased the time pilots maintained cognitive performance and arterial oxygen saturation upon high G-force exposure (greater than 9 G).[48] A more recent study indicated that G-suit inflation can cause changes to brain function that vary depending on the degree of inflation. Although this may reflect changes in cognitive processes,[47] implications of these changes are unclear. Additionally, the study did not involve testing in a high G-force environment, so it is unclear whether such changes apply during flight. Regarding implementation factors, one study reported that the timing of G-suit inflation—immediate versus delayed inflation after G-LOC—did not affect incapacitation time.[49] While these studies support the utility of G-suits, other studies have identified notable risks, including airway closure, air trapping in the lungs, and atelectasis (collapse of the lung) upon G-suit inflation,[50] as well as abdominal pain with extended-coverage G-suits, which provide more coverage of the lower body than standard G-suits.[51]

Anti-G-force Straining Maneuver

Another protective measure against G-LOC is the AGSM, which is commonly used along with G-suits. The AGSM is a technique during which the person pushes air out of the lungs against a closed glottis while simultaneously contracting the muscles in the calves, thighs, and shoulders to prevent blood pooling in the lower extremities.[29] Studies have long supported the value of the AGSM as a protective measure against G-LOC. In one study of U.S. Air Force fighter pilots from 1980-1999, 78 incidents of G-LOC occurred at an average of 8 G.[52] Poor execution of the AGSM was cited in 72% of the mishaps, while fatigue and G-suit malfunction were cited in 19% and low G-force tolerance in 14%. Studies comparing individuals who passed high G-force centrifuge training with those who did not have also consistently reported significantly lower rates of effective AGSM execution in those who did not pass the training.[6,29,53]

Centrifuge Training

The U.S. Air Force implemented human centrifuge training for pilots in the 1980s in response to reports of G-LOC-related accidents, with training priority going to those with fewer flying hours.[37,54] Studies have since shown that high G-force centrifuge training, often performed in combination with the AGSM or G-suits, can improve G-force tolerance.[55-57] During centrifuge training and with more flying hours, the repeated stimulation of the baroreceptor reflex, which helps regulate blood pressure in response to high G-force exposure, promotes cardiovascular adaptation to the G-forces seen during air combat maneuvers.[37,55,56,58,59]

Due to the level of evidence regarding these measures, all three are now standard components of G-force risk management strategies and G-force awareness training in the U.S. Air Force.[60] Collectively, studies suggest that the incidence of G-LOC and A-LOC appears to be declining due to improved training of pilots and crew, the correct execution of the AGSM, and the use of structured conditioning programs to increase the general strength of muscles involved in the AGSM.[3,6,45,53]

COGNITIVE AND BEHAVIORAL IMPACT OF MULTIPLE EXPOSURES

Cognitive Effects

Few studies have evaluated the cumulative effects of the hundreds of flights that fighter pilots undertake throughout their careers. It is not clear whether this frequent flying contributes to developing cognitive or behavioral signs consistent with brain injury or how frequently pilots fly before these signs occur. In fact, regarding the potential cognitive effects, one study reported better cognitive function among seasoned pilots than among novice pilots when assessing processing speed (via Stroop reaction time), suggesting cognitive adaptations occur with flying experience.[61] This finding is consistent with another study, which noted differences in functional connectivity in brain regions involved in motor, vestibular, and multisensory processing between fighter pilots and controls.[62] These observations suggest neuroplasticity helps pilots cope with the challenges of flight. However, other studies have reported notable cognitive impairments among military pilots. One study demonstrated that military pilots performed worse on tasks related to working memory than controls.[63] Additionally, these impairments were significantly correlated with functional changes in the hippocampus assessed using functional magnetic resonance imaging.[63] Collectively, these findings indicate that the cognitive effects of flight among military personnel, as well as the impact of flight on brain function, are likely domain specific and do not universally reflect impairment. Moreover, these findings have not been associated with deficits in the pilots' functional performance or long-term outcomes.

Effects on Mental Health and Behavior

Although some studies have reported on the incidence of mental health and behavioral issues among military pilots, no studies have specifically assessed the possible contribution of multiple high G-force exposures to these issues. In fact, some studies report a lower incidence of them among pilots than among those in other military occupations. One study used medical surveillance data from all U.S. Air Force members serving from October 2003 to December 2018 to compare the prevalence of mental health problems, behavioral health problems, sleep disorders, and fatigue between pilots and nonpilots.[64] The results showed that pilots (including manned aircraft pilots and remotely piloted aircraft pilots) had a significantly lower incidence of mental and behavioral health outcomes than those in all other U.S. Air Force occupations.[64] The study also showed a lower incidence of fatigue among pilots, even though the incidence of sleep disorder diagnoses was similar between the pilot and nonpilot groups. While these findings do not support a higher prevalence of behavioral or mental health problems among pilots, factors such as the stigma of reporting and receiving treatment for these issues may contribute to their underestimation among pilots.[65] Additionally, no studies have reported on differences in mental and behavioral health diagnoses between novice and experienced pilots, making it difficult to infer whether cumulative flight experience contributes to changes in those areas over time.

Considerations for Future Studies

Given the current state of research in this area, there is a clear need for large prospective studies to define the long-term psychological, cognitive, and behavioral impacts of multiple exposures to high G-forces. Ideally, such studies should utilize validated tools for measuring cognitive, behavioral, and psychological health symptoms, as well as blood biomarkers of brain injury and advanced functional and anatomic brain imaging to assess physiologic adaptations to multiple high G-force exposures. To clarify the specific contribution of high G-force exposure to these long-term risks among pilots, these studies should aim to carefully control for confounding factors, such as the stress of the military environment, as much as possible. This could be achieved by comparing pilots with nonpilots within specific military branches, rather than comparing military pilots with civilian controls. Such studies should also identify optimal protective anti-G-force strategies that pilots can use to minimize long-term health risks.

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