Cerebral oxygenation responses to aerobatic flight

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Abstract

Background: Aerobatics pilots must withstand high and sudden acceleration forces (Gz) up to ±10 Gz. The physiological consequences of such a succession of high and abrupt positive and negative Gz on the human body over time remain mostly unknown. This case report emphasizes changes in physiological factors such as cerebral oxygenation and heart rate dynamics collected in real aerobatic flights.

Case Report: A 37-year-old man, experienced in aerobatic flying, voluntarily took part in this study. During two flight runs (15-20 min), the pilot performed aerobatic maneuvers with multiple high (±10 Gz) positive and negative accelerations. He wore during the flights a Polar heart rate sensor while cerebral oxygenation was measured continuously over his prefrontal cortex via near-infrared spectroscopy (NIRS). NIRS allows for measurement of the relative concentration changes of oxygenated hemoglobin (O_2Hb) and deoxygenated hemoglobin (HHb) making it possible to determine cerebral oxygenation and hemodynamic status.

Discussion: The continuous in-flight monitoring of O_2Hb and HHb revealed the large effects of successive positive and negative Gz exposures on the cerebral hemodynamics alterations. The results showed a significant and positive correlation between changes in Gz exposures and O_2Hb concentration. This case report highlights that NIRS provides some valuable and sensitive indicators for the monitoring of cerebral hemodynamics during aerobatic flights exposed to multiple and high acceleration forces. To our knowledge, this first study quantifying cerebral oxygenation changes in aerobatic opens the way for the assessment of individual physiological responses and tolerance in pilots to repeated high Gz during real flights.

Keywords: near-infrared spectroscopy, monitoring, acceleration, heart rate, blood volume

Introduction

During their flight maneuvers, aerobatic pilots are facing high and sudden accelerations (load factors or G-loads) of short duration with rapid changes of direction in the longitudinal axis of the body.[1] In aerobatics, the Extra 330SC aircraft commonly used in the elite team can support ±10 Gz. A positive acceleration force (+Gz) exposure is known to induce a rapid decrease of blood pressure in the head.[9] Positive accelerations generate a hydrostatic gradient pressure directed downward, which forces the column of blood to move from the head to the feet. It results in reduced cerebral blood pressure. To maintain cerebral perfusion and counteract this hydrostatic pressure gradient, an increase in vascular resistance is produced by vasoconstriction while heart rate (HR) increases briskly. Conversely, bradycardia is associated with negative acceleration force (–Gz) where the column of blood moves to the head.[1] These changes of G-loads induce the push-pull effect, defined as a decrease +Gz tolerance caused by previous baseline zero or –Gz exposure. This effect can lead to a G-induced loss of consciousness (G-LOC) and mortal accident. G-LOC was reported most frequently over +5 Gz, and push-pull phenomenon was associated with 31.3% of G-LOC events and not considered an issue by 50% of individuals.[4]

Near-infrared spectroscopy (NIRS) is a common non-invasive method that provides continuous monitoring of the brain oxygenation state in ecological settings in humans.[11] NIRS measures the concentration of oxygenated (O_2Hb) and deoxygenated (HHb) blood thus allowing for the assessment of tissue oxygen saturation and total hemoglobin (tHb) concentration considered an equivalent of blood volume. NIRS has the advantages of: low interference with systems electromagnetic; acceptable signal to noise ratio when the subject is moving; great flexibility and accessibility of use; wireless portability and use in a natural environment.[11]

First measurements of cerebral oxygenation depending on load factors up to +3 Gz collected with NIRS were carried out when sitting in a human centrifuge.[2,3] These first studies showed a decrease in tHb with increasing load factors, accompanied by a greater decrease in oxygenated blood in comparison with deoxygenated blood that remained rather stable; thereby leading to a decrease in cerebral oxygen saturation level. In real flight, changes in cerebral oxygenation measured by NIRS was found to be related to positive accelerations (up to +9.5 Gz) in fighter jet pilots with an anti-G suit.[8] These results indicate that O_2Hb, tHb and the cerebral oxygenation saturation index decreased proportionally with exposure to continuous positive load factors. During parabolic flights, it was observed an O_2Hb decrease by 1.44 $\mu mol.L^{-1}$ from hypergravity (+1.8 Gz) followed by an important increase of 5.34 $\mu mol.L^{-1}$ during microgravity (0 Gz) episode.[12] Altogether, these studies underlie that NIRS is a feasible and sensitive method for assessment of brain blood oxygenation in an environment with positive G-forces changes.

However, changes in cerebral hemodynamics according to sudden and repeated exposures of both high positive and negative load factors over a flight bout have not been documented yet. The consequences in alternating high positive (e.g. maneuvers such as upright banks, turns and dive pullouts) and negative (e.g. maneuvers such as pushovers, outside loops) load factors as encountered in aerobatic pilots on the changes in cerebral oxygenation in a real flight are yet to be assessed. This current lacking information will help to better account for their physiological responses and tolerance ability to challenging flights. To date, there is very limited information regarding cerebral oxygenation monitoring in aerobatic pilots.[7] Several exposures to high +Gz forces can severely decrease cerebral blood perfusion and cause rapid G-LOC. Tolerance to high –Gz has been less studied due to severe congestion of blood in the head and uncomfortable symptoms.

This case report details changes in cerebral oxygenation and heart rate dynamics in one well-experienced pilot during aerobatic training bouts generating repeated and intense episodes of positive and negative load factors.

Case Report

The pilot was a man from the French Air Force Aerobatic Team (Equipe de Voltige de l'Armée de l'Air) aged 37 years old and had an aerobatic experience of 10 years. He was in good health and practiced almost every day sports activity (resistance and endurance training). He had his own physical and mental preparation-training program. The data were collected non-invasively during some flight training runs that the pilot would have undertaken in the absence of the experiment. The pilot was briefed on the protocol and signed an informed consent form before the start of the study and the measurement protocols followed the tenets of the Declaration of Helsinki.

The measurements took place in Salon de Provence (military base 701, France) on the first week of the 2020 training season. In agreement with his coach, the pilot had his own flight-training program over the week. Two different representative flight runs throughout the week were selected for data collection. Noteworthy the aerobatic figures were not the same and were not linked in the same way depending on the run. Thus, the intensities and the durations of positive and negative accelerations occurring during the two runs were not alike. Each flight lasted approximately 15-20 min. Some physiological and G-load features of the flights are presented in **Table I**. The pilot reported no greyout symptoms or loss of peripheral vision after the flights. The pilot had no anti-G suit and had no oxygen supply during the flights. The pilot did not wear a helmet to allow for the NIRS probes to be put over the skin of the forehead with sufficient comfort. Of note that the pilot was accustomed to fly without a helmet during his training periods.

[Table I here]

Cerebral oxygenation was measured using a NIRS system with 8 continuous-wave channels (Octamon, Artinis Medical System, Netherlands) positioned over the forehead region at approximately 2 centimeters above the eyebrows. This system firmly attached with a headband consists of two receivers (photodiodes with ambient light protection) and eight transmitters (1x4 for each hemisphere) placed at a uniform separation distance of 35 mm while avoiding the region of the temporal muscles. The transmitters (light-emitting diodes) send a near-infrared light at two known wavelengths (751 nm and 839 nm) to determine optical density variations and provide information on local fluctuations in the concentration of O_2Hb and HHb using the modified Beer-Lambert law. To protect from external light and movement interferences over the skin, the headband was further covered using a bandana. Sampling frequency was set at 10 Hz. The cerebral oxygenation variables (O_2Hb, HHb, tHb) collected during the flights were averaged across the 8 channels put on the forehead. Heart rate was recorded continuously by a dedicated HR monitor (H10, Polar Electro, Oy, Finland) positioned on the chest. Finally, the aircraft's accelerations, which designated G-loads, were measured using an inertial measurement unit (MPU 9250, InvenSense Inc.; sampling frequency of 100 Hz) fixed inside the aircraft, being as close as possible to the pilot. All data were collected and synchronized by smartphones (Google Pixel 3, China).

Fig 1. and **Fig 2**. show the physiological and acceleration measurements during the two flight bouts. They represent the dynamic changes of [O_2Hb] and heart rate in time with G-loads throughout the aerobatic flights.

Changes in HR followed the profile of G-loads while the latter was mirrored in the changes of oxyhemoglobin concentration. The results of the Pearson’s correlation showed a significant negative correlation ($r = -0.67$, $p < 0.001$) between both changes in O_2Hb and G-factors, indicating that G-factors explained 45% of the variance in O_2Hb concentration.

[Fig. 1 here]

[Fig. 2 here]

Aerobatic runs had a significant impact on the cardiovascular system. The pilot was facing significant decreases and increases in HR within a short period of time. A difference of 50 bpm and 63 bpm was observed between the minimum and maximum values of HR during flight bouts 1 and 2, respectively.

Discussion

In this case report, we present the first study monitoring the changes of cerebral oxygenation and heart rate in one experienced-acrobatic flight pilot in response to the exposures of high and abrupt positive and negative accelerations for a period of around 20 min during two training flights.

The main results of this study are the consistent decreases of O_2Hb on each positive acceleration exposure and the increases of O_2Hb on each negative acceleration, producing almost a mirror image of the Gz profile. Further, the changes in HHb showed small increases during negative load factors while they remained quite stable during positive ones. The results in this case report point out strong variations in the status of cerebral oxygenation, revealing occurrences of short hypoxia or hyperoxia epochs depending on load factors exposure. First, positive accelerations negatively did impact the cerebral oxygenation. We suggest that there is likely a reduction in arterial flow to the brain on each +Gz load but not a simple shift in blood volume away from the head. This result is in agreement with previous observations performed either during simulations in centrifuges[2,3] or during various real flight conditions (aerial gunnery training,[8] parabolic[12]). In addition, we noticed during –Gz exposure a very wide increase of O_2Hb regarding the baseline level (resting), much more intense than for the decrease of O_2Hb during +Gz exposure (see Fig. 1 and Fig. 2). Indeed, the maximum increase (**Table I**) was roughly four times greater than the maximum drops in O_2Hb.

Second, the increase of O_2Hb with only small HHb elevation during –Gz indicated that negative accelerations do not imply a simple phenomenon of blood returning to the head. This phenomenon as noted by Schneider et al.[12] during a moderate change from +1.8 Gz to 0 Gz (parabolic flight) could reflect an increase in the carotid flow. Moreover, the increase in O_2Hb could be due to a reduction in venous return inherent to the gradient of the hydrostatic pressure directed towards the head during –Gz events.[6] Also, the immediate effects of –Gz load factors are known to increase the arterial pressure above the heart level[7] and in turn produce a slowing in HR as we observed in the present study.

Importantly, this case report shows that the minimal value of O_2Hb does not appear necessarily with the occurrence of maximal G-factor value, like the maximal O_2Hb does not come up with the minimal G-factor. More than the magnitude *per se* of the load factor, its duration could have greater impacts on cerebral oxygenation alterations (**Table II**). The durations (in seconds) of the G-loads were calculated by taking into account successive values below the 0-Gz threshold for negative accelerations and above the 1-Gz threshold for positive accelerations. These durations were determined at remarkable values (i.e., lowest and highest values) of O_2Hb and Gz. The maximum decrease in the concentration of O_2Hb can be found at positive acceleration 20 % (flight 1) or 60% (flight 2) less intense than the highest +Gz value (noted “A” in Fig. 1 and Fig. 2). However, these relatively smallest acceleration values in terms of magnitude, lasted 2.3 times (flight 1) and 4.6 times (flight 2) longer than the duration corresponding to the maximum +Gz values. The same observation can be made for the maximum increase in the concentration of O_2Hb in response to negative accelerations during the second flight. Its value was 20% smaller than the lowest –Gz value, but 2.4 times longer (noted “B” in Fig. 2). In flight 1, the maximal increase in the concentration of O_2Hb

did match with the lowest –Gz value. Regarding positive load factors, our results agree with those of Kobayashi and Miyamoto.[8] The authors observed in a pilot wearing an anti-G suit an O_2Hb decrease up to 14 µmol.L^{-1} during a prolonged acceleration of approximately +4 Gz over a period of 1 minute 30 s, while O_2Hb dropped by 6.5 µmol.L^{-1} for an acceleration of +6.8 Gz during 10 seconds. Concerning the negative load factors, the original values reported in this case report suggest that the –Gz tolerance for the experienced aerobatic pilot was high as compared to the known limits of human tolerance to Gz as determined in a large centrifuge.[10]

Overall, these results indicate an increased risk of undesirable physiological events such as loss of vision or loss of consciousness when the time spent under high load factors increases.[1]

[Table II here]

In addition, this case report highlights the importance of the sequences of positive and negative load factors on changes in cerebral oxygenation and heart rate. By comparing the two flights, we can observe a difference of 3.43 µmol.L^{-1} in O_2Hb max. While we expect a longer and/or a more intense G-load for the greatest increase of concentration of O_2Hb, the opposite occurred (**Table II**). The best explanation is likely the sequence order of accelerations: there is a direct sequence of 2 negative aerobatics maneuvers for the 2nd flight while there is a longer interval of time between two consecutive maneuvers concerning flight 1 with an acceleration that comes back close to 1 Gz. Therefore, it appears important to take into account the order of the aerobatics maneuvers (i.e. oscillating positive to negative Gz transitions and vice-versa) for a better understanding of potential alterations in physiological responses and tolerance. In fact, blood pressure is greatly reduced under positive acceleration when pre-acceleration is negative. This can lead to a reduced +Gz tolerance (push-pull effect) and an increased risk of G-LOC.[5] Consequently, vasoconstrictor response is a critical adaptive mechanism during +Gz when preceded by –Gz exposures. Our in-flight monitoring, in which no deleterious effects occurred, suggests that the experienced aerobatic pilot with good physical conditioning was well accustomed to various sustained Gz exposures. Also, certain aerobatics tricks requiring skilled maneuvers during the flight might promote a better Gz tolerance.

We cannot draw any conclusions from this single case report because of several limitations and methodological considerations. Only the z-axis of gravity was considered in the present study. However, the other axes of acceleration (Gx: forward and backward; and Gy: left and right lateral) can have repercussions on the hydrostatic pressure, and in turn may influence the cerebral oxygenation and heart rate dynamics.[9] Further studies are needed to look after these axes and to investigate the importance of acceleration sequences (time and intensities) in the physiological responses of aerobatics pilots.

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Tables

Table I. Features (maximal and minimal values) of oxygenated blood (O_2Hb), heart rate (HR) and G-loads (Gz) in the two training flights.

Variables	Flight 1	Flight 2
Gz max	8.1	8.6
Gz min	-5.7	-6.2
O_2Hb max ($\mu mol.L^{-1}$)	44.57	48
O_2Hb min ($\mu mol.L^{-1}$)	-12.62	-8.25
HR max (bpm)	116	127
HR min (bpm)	66	64

Table II. Period of time for G-loads (calculated below 0-Gz threshold for -Gz and above 1-Gz threshold for +Gz) and values of Gz and O_2Hb associated with remarkable values (min and max) of O_2Hb and Gz.

	Flight 1				Flight 2			
Associated with	Gz max	Gz min	O_2Hb max	O_2Hb min	Gz max	Gz min	O_2Hb max	O_2Hb min
Duration of G-load (sec)	4.0	12.5	12.5	9.3	3.6	4.5	10.8	16.7
Gz	8.1	-5.7	-5.7	6.5	8.6	-6.2	-5.0	3.24
O_2Hb ($\mu mol.L^{-1}$)	-8.34	44.57	44.57	-12.62	-7.0	42.7	48.0	-8.25

Figure captions

Figure 1. Cerebral oxygenation (O_2Hb in µmol.L^{-1}) and heart rate (HR, bpm) changes in time with load factors (Gz) during the flight 1. The circles identify the highest and lowest values for each time course. A corresponds to a G-value of 6.48 Gz at the lowest O_2Hb.

Figure 2. Cerebral oxygenation (O_2Hb, µmol.L^{-1}) and heart rate (HR, bpm) changes in time with load factors (Gz) during the flight 2. The circles identify the highest and lowest values for each time course. A corresponds to a G-value of 3.2 Gz at the lowest O_2Hb. B corresponds to a G-value of -5.0 Gz at the highest O_2Hb.