Cerebral Oxygenation Responses to Aerobatic Flight

Eléonore Fresnel; Gérard Dray; Simon Pla; Pierre Jean; Guilhem Belda; Stéphane Perrey

BACKGROUND: Aerobatic pilots must withstand high and sudden acceleration forces (G_z) up to ±10 G_z. The physiological consequences of such a succession of high and abrupt positive and negative G_z 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-yr-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 G_z) positive and negative accelerations. During the flights he wore 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 G_z exposures on cerebral hemodynamics alterations. The results showed a significant and positive correlation between changes in G_z 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 aerobatics opens the way for the assessment of individual physiological responses and tolerance in pilots to repeated high G_z during real flights.

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

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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 G_z. A positive acceleration force ($+G_z$) 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 ($-G_z$), where the column of blood moves to the head.[1] These changes of G loads induce the push-pull effect, defined as a decrease $+G_z$ tolerance caused by previous baseline zero or $-G_z$ exposure. This effect can lead to a G-induced loss of consciousness (G-LOC) and fatal accident. G-LOC was reported most frequently over +5 G_z 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 noninvasive method that provides continuous monitoring of the brain oxygenation state in ecological settings in humans.[11] NIRS

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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 electromagnetic systems; acceptable signal to noise ratio when the subject is moving; great flexibility and accessibility of use; and wireless portability and use in a natural environment.[11]

The first measurements of cerebral oxygenation depending on load factors up to +3 G_z collected with NIRS were carried out while 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 were found to be related to positive accelerations (up to +9.5 G_z) 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, an O_2Hb decrease by 1.44 $\mu mol \cdot L^{-1}$ was observed from hypergravity (+1.8 G_z) followed by an important increase of 5.34 $\mu mol \cdot L^{-1}$ during microgravity (0 G_z) episodes.[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 force changes.

However, changes in cerebral hemodynamics due 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 by 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 $+G_z$ forces can severely decrease cerebral blood perfusion and cause rapid G-LOC. Tolerance to high $-G_z$ 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) who was 37 yr old and had an aerobatic experience of 10 yr. He was in good health and practiced sports activities (resistance and endurance training) almost every day. He had his own physical and mental preparation training program. The data were collected noninvasively 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) in 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. Of note, 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. It should be noted that the pilot was accustomed to fly without a helmet during his training periods.

Cerebral oxygenation was measured using a NIRS system with eight continuous-wave channels (Octamon, Artinis Medical Systems, Elst, Gelderland, Netherlands) positioned over the forehead region at approximately 2 cm above the eyebrows. This system, firmly attached with a headband, consists of two receivers (photodiodes with ambient light protection) and eight transmitters (1 × 4 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 eight channels on the forehead. Heart rate was recorded continuously by a dedicated HR monitor (H10, Polar Electro Oy, Kempele, Finland) positioned on the chest. Finally, the aircraft's accelerations, which caused the G loads, were measured using an inertial measurement unit (MPU 9250, InvenSense Inc., San Jose, CA, USA; sampling frequency of 100 Hz) fixed inside the aircraft,

Table I. Features (Maximal and Minimal Values) of Oxygenated Blood (O_2Hb), Heart Rate (HR), and G Loads (G_z) in the Two Training Flights.

VARIABLES	FLIGHT 1	FLIGHT 2
G_z max	8.1	8.6
G_z min	−5.7	−6.2
O_2Hb max ($\mu mol \cdot L^{-1}$)	44.57	48
O_2Hb min ($\mu mol \cdot L^{-1}$)	−12.62	−8.25
HR max (bpm)	116	127
HR min (bpm)	66	64

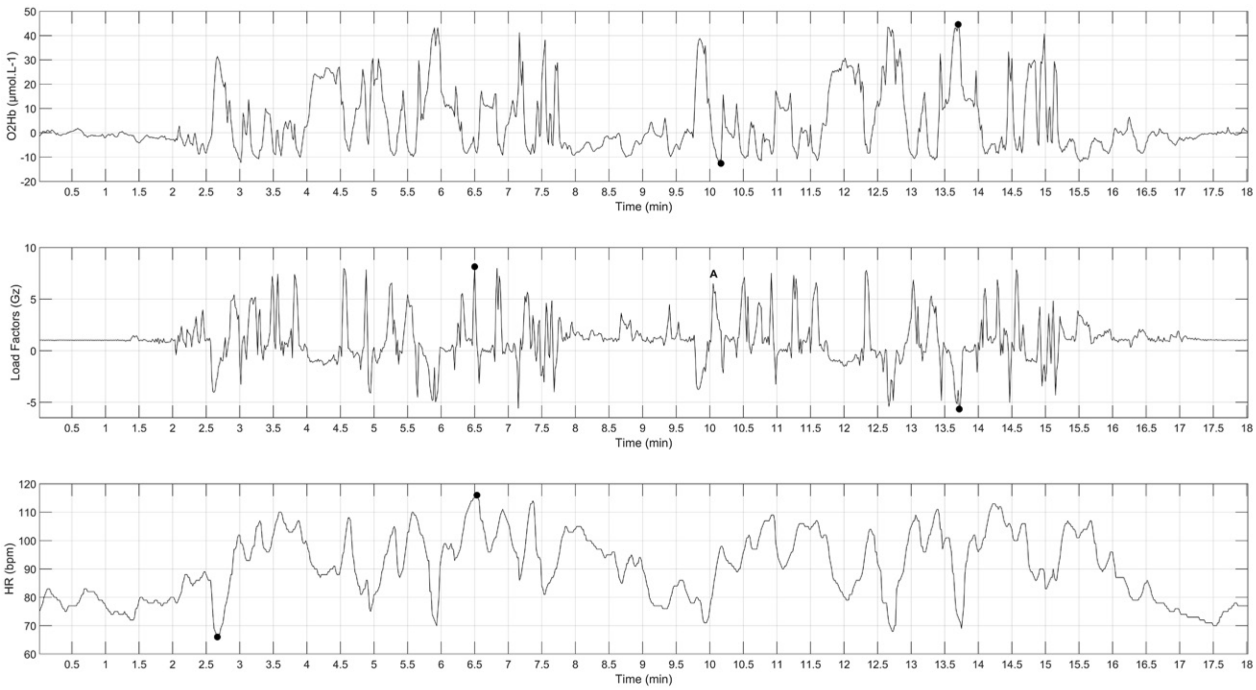

Fig. 1. Cerebral oxygenation (O_2Hb in µmol · L^{-1}) and heart rate (HR, bpm) changes in time with load factors (G_z) during flight 1. The circles identify the highest and lowest values for each time course. A corresponds to a G value of 6.48 G_z at the lowest O_2Hb.

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.

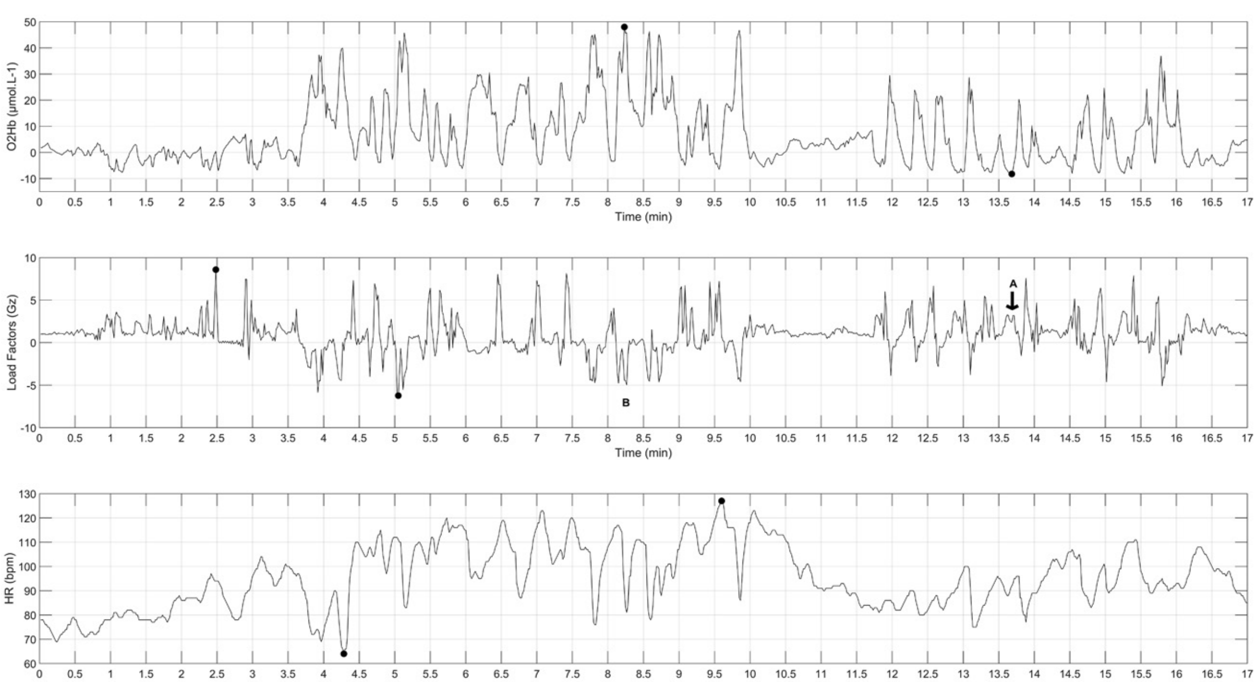

Fig. 2. Cerebral oxygenation (O_2Hb, µmol · L^{-1}) and heart rate (HR, bpm) changes in time with load factors (G_z) during flight 2. The circles identify the highest and lowest values for each time course. A corresponds to a G value of 3.2 G_z at the lowest O_2Hb. B corresponds to a G value of −5.0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

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 G_z 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 factor exposure. First, positive accelerations did negatively impact cerebral oxygenation. We suggest that there is likely a reduction in arterial flow to the brain on each $+G_z$ 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, during $-G_z$ exposure, we noticed a very large increase in O_2Hb compared to the baseline level (resting), much more intense than for the decrease of O_2Hb during $+G_z$ 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 $-G_z$ 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 G_z to 0 G_z (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 toward the head during $-G_z$ events.[6] Also, the immediate effects of $-G_z$ 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 minimum value of O_2Hb does not necessarily appear with the occurrence of maximum G, just as the maximum O_2Hb did not come up with minimum G. 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 considering successive values below the 0-G_z threshold for negative accelerations and above the 1-G_z threshold for positive accelerations. These durations were determined at specific values (i.e., lowest and highest values) of O_2Hb and G_z. 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 $+G_z$ value ("A" in Fig. 1 and Fig. 2). However, these relatively small 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 $+G_z$ 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 $-G_z$ 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 $-G_z$ value. Regarding positive load factors, our results agree with those of Kobayashi and Miyamoto.[8] In a pilot wearing an anti-G suit, the authors observed an O_2Hb decrease up to 14 $\mu mol \cdot L^{-1}$ during a prolonged acceleration of approximately +4 G_z over a period of 1 min 30 s, while O_2Hb dropped by 6.5 $\mu mol \cdot L^{-1}$ for an acceleration of +6.8 G_z during 10 s. Concerning the negative load factors, the original values reported in this case report suggest that the $-G_z$ tolerance for the experienced aerobatic pilot was high as compared to the known limits of human tolerance to G_z 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] 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 $\mu mol \cdot L^{-1}$ 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 second flight while there is a longer interval of time between two consecutive maneuvers concerning flight 1 with an acceleration that comes back close

Table II. Period of Time for G Loads (Calculated Below the 0-G_z Threshold for $-G_z$ and Above the 1-G_z Threshold for $+G_z$) and Values of G_z and O_2Hb Associated with Remarkable Values (Min and Max) of O_2Hb and G_z.

	FLIGHT 1				FLIGHT 2			
ASSOCIATED WITH	G_Z MAX	G_Z MIN	O_2HB MAX	O_2HB MIN	G_Z MAX	G_Z MIN	O_2HB MAX	O_2HB MIN
Duration of G load (seconds)	4.0	12.5	12.5	9.3	3.6	4.5	10.8	16.7
G_z	8.1	−5.7	−5.7	6.5	8.6	−6.2	−5.0	3.24
O_2Hb ($\mu mol \cdot L^{-1}$)	−8.34	44.57	44.57	−12.62	−7.0	42.7	48.0	−8.25

to 1 G_z. Therefore, it appears important to consider the order of the aerobatics maneuvers (i.e., oscillating positive to negative G_z 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 preacceleration is negative. This can lead to a reduced $+G_z$ tolerance (push-pull effect) and an increased risk of G-induced loss of conciousness.[5] Consequently, vasoconstrictor response is a critical adaptive mechanism during $+G_z$ when preceded by $-G_z$ 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 G_z exposures. Also, certain aerobatics tricks requiring skilled maneuvers during the flight might promote a better G_z 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 (G_x: forward and backward; and G_y: left and right lateral) can have repercussions on the hydrostatic pressure and, in turn, may influence cerebral oxygenation and heart rate dynamics.[9] Further studies are needed to look at these axes and to investigate the importance of acceleration sequences (time and intensities) in the physiological responses of aerobatics pilots.

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