INTEGRATIVE PHYSIOLOGY-COUPLED PILOT-CENTERED FLIGHT SIMULATION

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ABSTRACT

This research focuses on coupling the FlightGear flight simulator and Pulse physiology engine applications to recreate and understand hypoxic events, related to a combination of high FiO2 and high g-forces. Global data is shared between the FlightGear and Pulse by creating interdependency between the two applications known as coupling. By coupling interactive simulations based on FlightGear and Pulse, hypoxic events were recreated from two scenarios: simulated acceleration atelectasis, achieved by using high g-forces output from FlightGear with a modified Pulse tension pneumothorax scenario, and the combination of high g-forces and high FiO2, based on a prototype OBOGS simulation. To validate hypoxia based on each scenario, pulmonary ventilation (V)-capillary perfusion (Q) ratios are evaluated to determine if there is a V/Q mismatch caused by a reduction in ventilation.

Keywords: accelerated atelectasis, FiO2, FlightGear, OBOGS, Pulse Physiology Engine, tension pneumothorax, V/Q mismatch.

1 INTRODUCTION

High-performance aircraft were built to endow fighter pilots the ability to engage in air-to-air combat in flight while maintaining the human physiological performance envelope. According to National Aeronautics and Space Administration (NASA) Earth's atmosphere is composed of approximately 78% Nitrogen, 21% Oxygen, 0.93% Argon, 0.04% Carbon dioxide, and trace amounts of neon, helium, methane, krypton, hydrogen, and water vapor (Buis 2009). Due to the decrease in atmospheric pressure as altitude increases, defined by Boyle's (gas) law, fewer molecules are present in a given volume of air, therefore, decreasing effective oxygen as altitude increases, as seen in Figure 1. The effects of this property require that high-performance aircraft be equipped with an OBOGS which acts a life support in hypoxic environments by enabling oxygenation of the bloodstream in the pilot (Sathlyaseelan 2014).

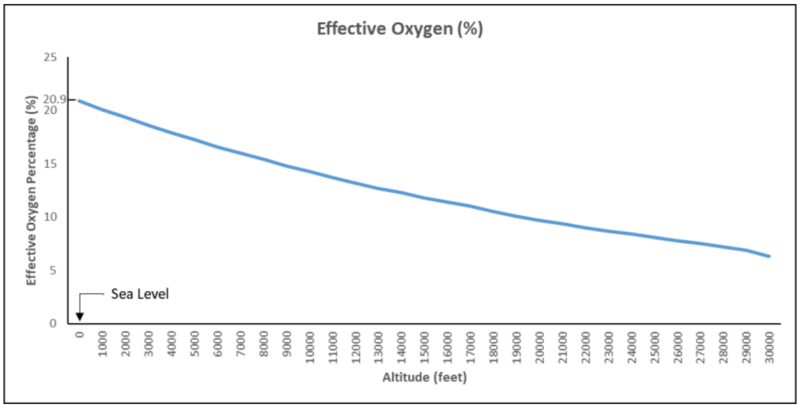


Figure 1: Effective Oxygen vs. Altitude.

The OBOGS provides breathable quality air with oxygen concentration and pressure breathing for altitude (PBA) for mask cavity pressure in inches-of water (inWg) to a fight aircraft with a ceiling of 50,000 feet or higher. The system is designed to maintain, at a minimum, alveolar oxygen tension of at least 100 mm HG and; blood oxygen saturation above 95%, while preventing the alveolar oxygen tension from falling below 30 mm HG on rapid decompression of the cabin when at least 95% oxygen is delivered to the mask automatically after the decompression (U.S. Department of Defense 2015). A minimum of 95% oxygen concentration is not only required upon cabin decompression but also for cabin altitude exceeding 25,000 feet which are both achieved by the automatic activation of emergency oxygen and manual activation for smoke and fumes in the cockpit. As depicted in Figure 2, the OBOGS is designed to restrict the concentration of oxygen to a maximum of 60% at cabin altitudes between 0 and 15,000 feet or 75% at a cabin altitude of 20,000 feet and momentary levels of 10 above the aforementioned maximum (U.S. Department of Defense 2015). For cabin altitudes over 25,000 feet emergency oxygen is provided of at least 99.5% oxygen concentration.

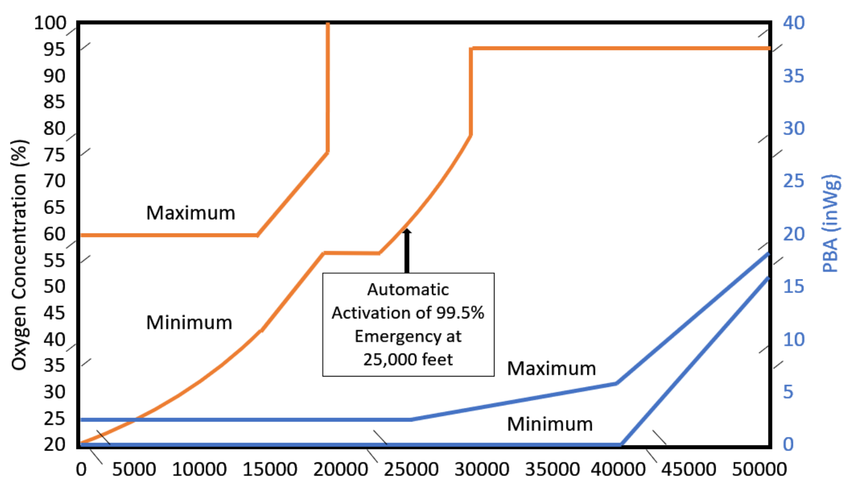


Figure 2: OBOGS oxygen concentration band: adapted from (U.S. Department of Defense 2015) by author.

In order to analyze hypoxic episodes in pilots, the FlightGear-based flight simulator has been coupled with the real-time Pulse based simulation. The coupled simulator is used to provide feedback for patient/pilot analysis based on high g-forces and high-altitude flight patterns simulated with a F-15 aircraft model. To model the absorption collapse of lung alveoli (total or partial) due to high g-forces, known as *acceleration atelectasis*, an open-source tension pneumothorax scenario, available in Pulse, is modified to simulate in-flight hypoxic events. Since tension pneumothorax typically occurs by an open chest wound or trauma to this region, this scenario must be adjusted to simulate atelectasis. Pulse implements both open and closed tension pneumothorax scenarios with control on the severity level based on chest wound size and the simulated support for needle decompression treatment (Pulse 2022). In our flight setting, the modified tension pneumothorax is triggered by dynamic high g-forces rather than trauma, while needle decompression is not applicable. Additionally, the open tension pneumothorax scenario, where external air enters the pleural cavity until equilibrium is reached with atmospheric pressure, is deemed inapplicable: closed tension pneumothorax is selected as basis for inducing atelectasis.

2 METHODS

The fundamental technique that enables this novel simulation protype is a software coupling mechanism, Transmission Control Protocol/Internet Protocol (TCP/IP), between FlightGear and Pulse-based real-time simulations. TCP/IP networking is a set of communication protocols used to establish and maintain end-to-end connections between applications, known as server and client, for exchanging data as depicted in Figure 3. Data transmitted by the server is assembled into smaller packets and reassembled by the client after receipt for processing. To provide high g-force data to Pulse, TCP/IP is used to design packets for sending data from FlightGear to Pulse. Within FlightGear, TCP/IP is configured as a unidirectional network connection to only transmit data through the interface port using localhost as the IP address since both applications are installed on the same machine. G-force, along with airspeed (for reference only) and altitude, values are transmitted to Pulse through the creation of an extensible markup language file (XML file) in the form of hierarchical elements.

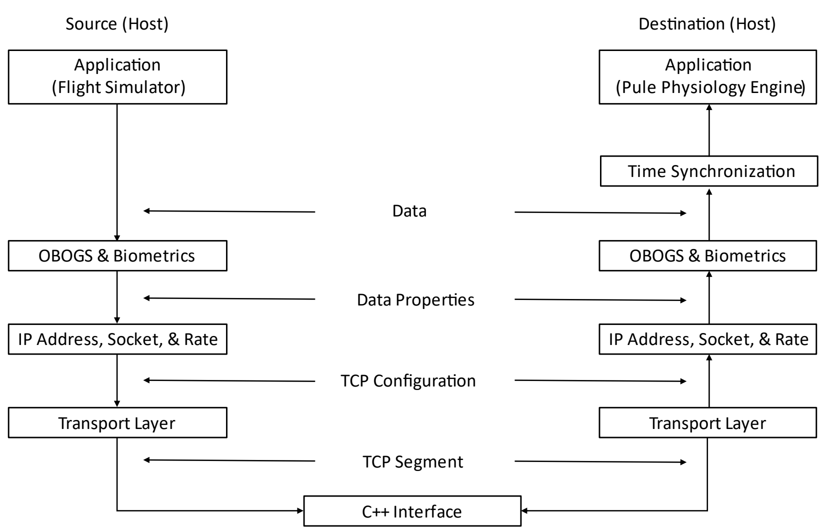


Figure 3: FlightGear and Pulse coupling using TCP/IP protocol.

Within Pulse open and closed (independently) Tension Pneumothorax scenarios can be implemented. Since open Tension Pneumothorax represents constant external air entering the body until reaching equilibrium with atmospheric pressure, closed Tension Pneumothorax is implemented for controlling the constant and dynamic pressures exerted on the lungs internal to the pleural cavity for inducing acceleration atelectasis. To correlate high g-force to acceleration atelectasis, g-force data transmitted from FlightGear an algorithm has been developed which assigns a severity value of acceleration atelectasis by calculating intrapleural pressure based on based g-force dependency, a pilot weighing approximately 77 kilograms, average lung surface area. Using altitude data, oxygen concentration is determined using a piecewise-interpolated second-order polynomial as the prototype OBOGS mathematical model.

FlightGear, or the server, is an open-source flight simulator that supports existing aircraft models, terrain, and customization for flying (FlightGear 2021). Pulse, or the client, is an open-source integrative human physiology simulator, which supports both standalone application or integration with other digital and analog peripherals (Pulse 2021). Pulse is designed to model the human physiology with the ability to function as a standalone application or integrate with other digital and analog peripherals. FlightGear and Pulse applications are implemented using the C++ (CPP) computing language. Using TCP/IP FlightGear and Pulse have been coupled for performing real-time analysis at a frequency of 1 Hertz in a single (Pulse) engine that allows modification to all physiological parameters simultaneously. While flying the McDonnell Douglas F-15 Eagle fighter aircraft on autopilot, airspeed, g-force, and altitude are transmitted to Pulse in a comma delineated string array for parsing. Due to Pulse's ability to process faster than real-time, Pulse is limited to 1 Hertz for synchronous processing with FlightGear. Currently the CPP implementation file within Pulse, also known as source code, executes TCP/IP while directly performing operations on the patient/pilot by parsing data in the form of a string array received from FlightGear.

A prototype OBOGS model has been developed to control the FiO2 up to an altitude of 35,000 feet. The model is a piecewise-interpolated second-order polynomial represented by Figure 4 that represents the oxygen concentration band for the OBOGS. Implementation of the prototype OBOGS model will maintain adequate supply of oxygen to the tissues of the body in case of reduction in barometric pressure consequent upon ascent to altitude, i.e., to prevent hypoxia (Sathiyaseelan 2014). Oxygen generated by OBOGS is produced by a concentrator which separates oxygen from nitrogen in ambient air with the use of a molecular sieve. In compliance with system design requirements, the Partial Pressure of Oxygen (PPO_2) produced by the concentrator is converted to a desired oxygen concentration band for inhalation dependent on altitude and transported by compressed air.

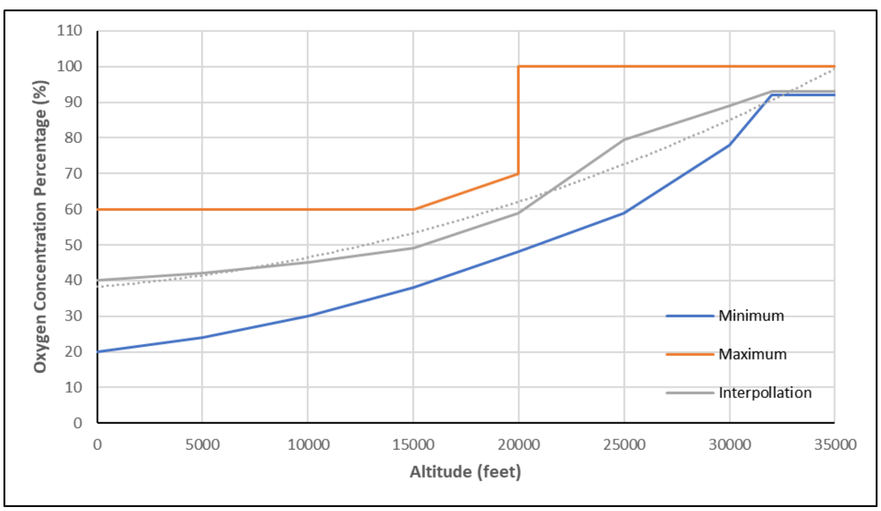


Figure 4: Interpolated OBOGS concentration band.

Nonetheless, the effects of high g-forces can result in accelerated atelectasis, a partial collapse of the lung alveoli, which reduces gas absorption during inhalation. To model accelerated atelectasis, a scenario of tension-pneumothorax is implemented in Pulse. In tension pneumothorax, air flows into the pleural cavity during inhalation but is retained in the pleural cavity during exhalation and thus cannot exit, leading to a gradual increase in intra-pleural cavity pressure (Choi 2014). Increased intra-pleural pressure resulting from tension pneumothorax can occur from spontaneous (without cause in a healthy individual) or traumatic (i.e., chest wound) pneumothorax. For a healthy subject undergoing tension pneumothorax, pleural cavity pressure ranges are simulated in Pulse by increasing the chest wound severity level from 0 to 1 in increments of 0.1. Considering intrapleural pressure in a healthy subject ranges from ~ -2 mmHg to ~ -7 mmHg, the resulting Pulse intrapleural pressures are valid, ranging from -4 mmHg to 3 mmHg. Instead of a chest wound, the tension pneumothorax trigger is based on g-force to induce accelerated atelectasis. This leads to increased pressure within the pleural cavity which ultimately defines g-force as being analogous to positive intrapleural pressure. Furthermore, sensitivity to g-force can be increased within the simulation. Since the pilot may not experience hypoxia by oxygen toxicity alone until after long term (14 hours) exposure, hypoxia results have been captured for acceleration atelectasis and high-FiO2 atelectasis while flying the Machynlleth Loop tactical training area at 30,000 ft using FlightGear. The Machynlleth Loop, officially known as Low Flying Area 7 (LFA 7), is located in central-Wales, UK, and is used by the Royal Air Force for low level flight and training.

The ratio or matching of pulmonary ventilation (V) and perfusion (Q) (V/Q) is used to quantitatively assess oxygen exchange and carbon dioxide elimination, as seen in Figure 5. The V/Q ratio in the base lung region has a low V/Q ratio of approximately 0.6, V/Q ratio in the middle lung region reaches 1.0 at the 3rd rib, and the apex region has a high V/Q ratio of 3.0. Observation of an impairment in ventilation or a decrease in perfusion in one or more lung regions a mismatch of V/Q ratio would be identified in these regions. By calculating the V/Q ratio, the pilot physiology can be analyzed to validate the cause of hypoxia due to oxygen toxicity and acceleration atelectasis. Pulse can be modified to compute the V/Q ratio as well as V/Q mismatch throughout the whole lung by aggregating total alveolar ventilation and mean pulmonary capillary flow. V/Q is then calculated using a moving average of the Pulse subject's V and Q rate values. Hypoxic events described in the results section are caused by a decrease in ventilation due to the effects of atelectasis and high-FiO2.

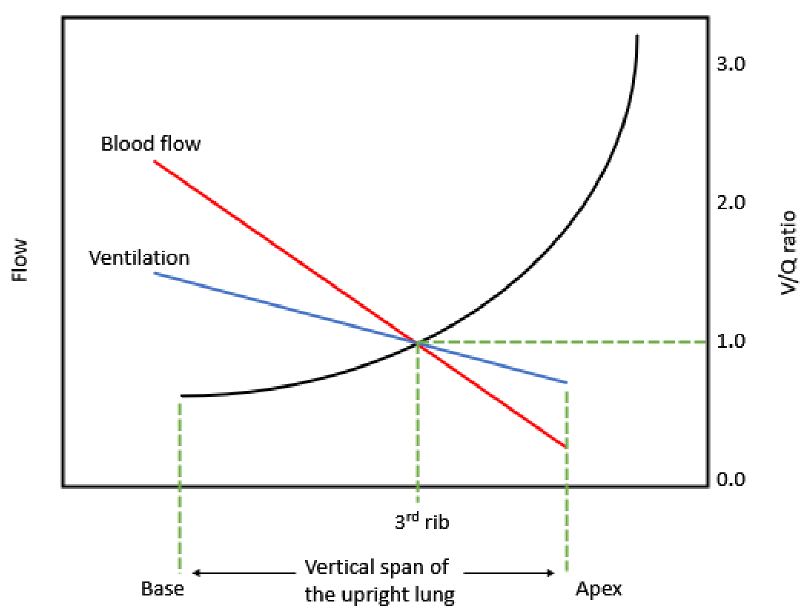
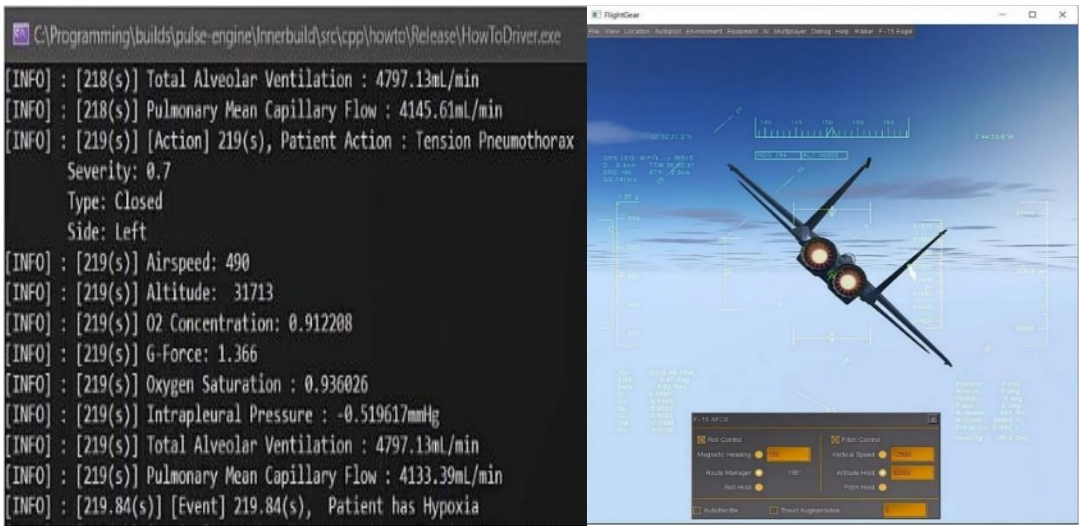


Figure 5: Ventilation-Perfusion Matching: adapted from (Yartsev 2022) by author.

3 RESULTS

As shown in Figure 6, FlightGear and Pulse were successfully coupled using the TCP/IP network communication protocol with airspeed, g-force, and altitude data transmitted from FlightGear and received by Pulse, both at a frequency of 1 Hertz. Shown in Figure 6(a), the associated data displayed when referencing the Pulse command prompt during execution is as follows: data received from FlightGear via TCP/IP, tension pneumothorax parameters, and V/Q ratio parameters. Furthermore, the visual flight dynamics available from FlightGear in Figure 6(b) corresponds to the data displayed in the Pulse command prompt.



(a) (b)

Figure 6: Hypoxia event and aircraft orientation using TCP/IP with (a) Pulse Physiology Engine (Server) and (b) FlightGear (Client).

As a baseline, the average V/Q ratio from Pulse is approximately 1.25 during steady and level flight at 30,000 feet and a g-force of 1. Figure 7 graphs the exposure of high g-forces from 144 seconds after flight and up until 208 seconds creates a significant change in V/Q ratio. Upon analyzing hypoxia based on high g-forces only, both V/Q mismatch and a hypoxia event occurs at 219 seconds when the V/Q ratio falls below 1.25 which is due to high-g maneuvers sustained throughout the latter section of the course. As high g-forces stabilize after the hypoxia event, V/Q mismatch approaches a normal V/Q ratio as indicated by the red region from 219 seconds to 249 seconds.

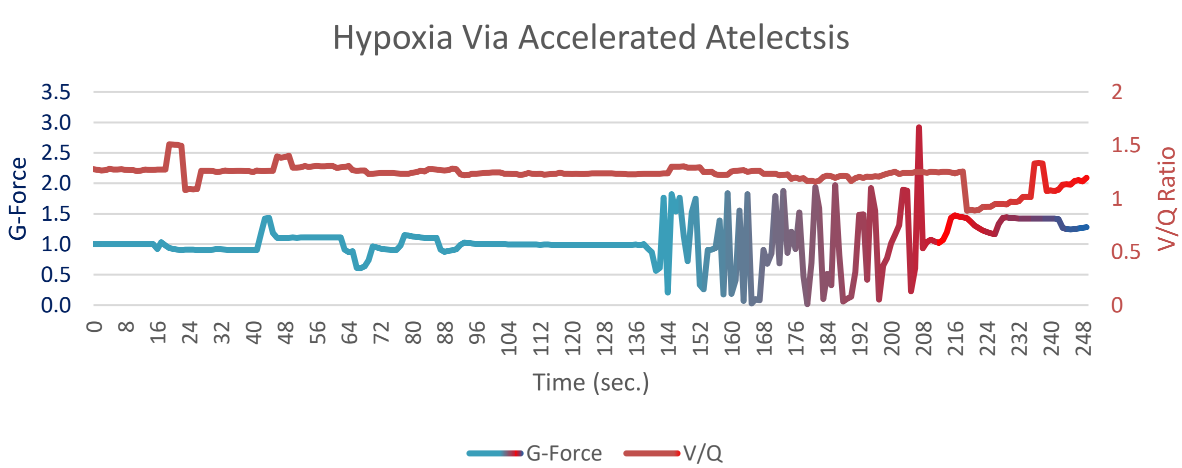


Figure 7: Hypoxia via high g-forces only. Red indicates areas of high g-force and V/Q mismatch.

Using altitude, FiO2 is calculated and updated in real-time within Pulse to simulate a prototype OBOGS which counteracts the inversely proportional relationship of altitude to FiO2. Figure 8 graphs the exposure of high g-forces from 120 seconds after flight and up until 190 seconds in conjunction to high-FiO2 throughout the flight duration creates a significant change in V/Q ratio. Upon analyzing hypoxia based on high g-forces and high-FiO2, V/Q mismatch and hypoxia occur at 190 seconds when the V/Q ratio falls below 1.25 which is due to high-g maneuvers sustained throughout the latter section of the course. In comparison to the previous scenario where hypoxia is induced by high g-forces alone, the added exposure to high-FiO2 creates an earlier onset of hypoxia. As high g-forces stabilize and a high-FiO2 is sustained after the hypoxia event, V/Q mismatch approaches a normal V/Q ratio as indicated by the red region from 190 seconds to 219 seconds.

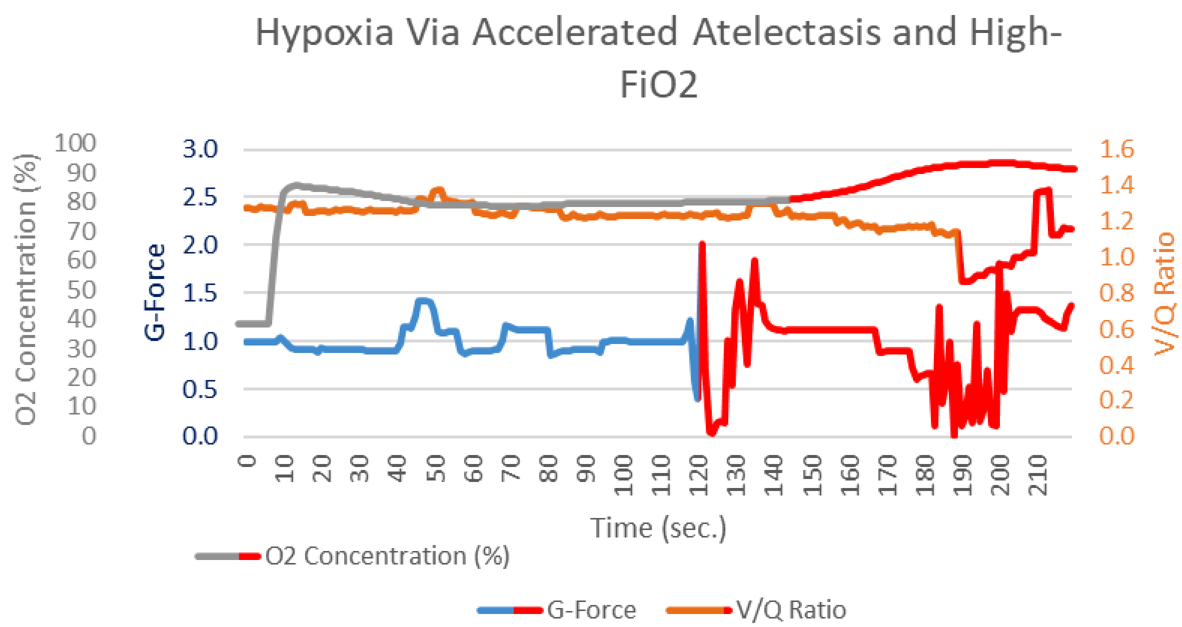


Figure 8: Hypoxia via high g-forces and high-FiO$_2$. Red indicates areas of high g-force, V/Q mismatch and high-FiO2.

4 CONCLUSION AND FUTURE WORK

Successful coupling of FlightGear with Pulse has been used to recreate and analyze hypoxia due to high g-force and high FiO2 among high-performance aircraft pilots. Each scenario resulted in hypoxic events that confirm high g-forces and high FiO2 are contributing factors for hypoxia when pilots are unable to maintain the physiological envelope. These findings coincide with a limited study using a single acceleration level and O2 concentration with hypoxia occurring after 60 seconds, where changes in either will alter the extent to which acceleration atelectasis develops (Pollock et al. 2022). Using V/Q ratio to validate hypoxia, each scenario resulted in a V/Q mismatch below the Pulse baseline due to a reduction in pulmonary ventilation.

Since the current OBOGS system design only provides oxygen when demanded by inhalation, the prototype OBOGS simulation can be improved by implementing Pulse's volume control - assist control (VC-AC) mechanical ventilator. This feature will allow configuration of ventilator settings such as inspiration waveform, expiration waveform, peak inspiration pressure, positive end expired pressure, and respiration periods, specific to modern OBOGS designs.

To improve the simulation of acceleration atelectasis, further refinements to the tension pneumothorax scenario are necessary. Future developments include validating the correlation of g-forces to atelectasis severity. Furthermore, the Pulse Physiology Engine does not model the discrete lobes of each lung. Instead, Pulse distributes the total volume for both lungs into two (left and right) volume lobes, with a default value of 52.5% for the right lung, resulting in 47.5% for the left lung. For this reason, Total Alveolar Ventilation/Pulmonary Mean Capillary Flow is calculated across both lung regions for determining when a mismatch occurs. Eventually, a detailed atelectasis simulation founded on multi-physics finite elements is planned, where real-time efficiency is feasible through a deep neural network implementation. Using neural networks based on biometrics and preexisting health conditions, if any, will result in the development of a predictive analytics model to determine if pilots are susceptible to hypoxia prior to flight.

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