Business & Commercial Aviation

Exploring High-Altitude Physiology

By Robert N. Rossier/Business & Commercial Aviation

The other day we had a little celebration. My friend Charlie Gray successfully climbed to the summit of Aconcagua, a 22,831-foot peak in Argentina that marks the highest point on the continent of South America. We received word of his arrival at the summit by satellite phone, and he described the scene in an elated, albeit winded tone. It was quite an accomplishment. Three years prior, he summitted Mount McKinley, the highest peak in North America, stretching 20,320 feet into the Alaskan sky. Along the way he suffered minor frostbite, and a bout with high-altitude pulmonary edema (HAPE) -- a condition wherein fluid accumulates in the lungs in response to exposure to the rarefied atmosphere. But these are just two of the potential problems faced by climbers as they tackle the higher elevations.

Both of these accomplishments came with time and hard work. Charlie trained for more than a year in preparation for each climb. He planned his expeditions as carefully as a moon mission. And he took more than a week to reach the summits -- a strategy designed to allow his physiology time to acclimate to the peculiarities of the thin air and harsh environment.

Reaching such altitudes in an airplane is commonplace. In the comfort of our warm, pressurized cockpits, we climb effortlessly to the flight levels in a matter of minutes. No special preparation or training is required. No acclimatization or physiological adaptation is necessary, and the planning for such an excursion is nothing if not routine. But if something runs amuck, such as a pressurization system failure, we could quickly find ourselves sucking thin air -- without the benefit of the training, preparation and acclimatization afforded my friend Charlie.

While Charlie was busy making his bid for the summit of Aconcagua, I too made a high-altitude ascent -- one that was dizzyingly fast. In a matter of minutes, I rocketed from sea level to an altitude of 25,000 feet, and despite the lack of oxygen, I didn't feel the least bit winded. But in a matter of minutes, my perceptions would begin to change. I felt slightly dizzy, but not alarmingly so. Picking up a clipboard, I began to answer a series of simple questions: my name, the altitude, something about the symptoms of hypoxia. I was reading the words, but they held no meaning. Somehow, I couldn't put them in context. Looking up, I realized my vision was becoming as fuzzy as my brain felt. Without knowing or caring, I was mentally slipping away, and doing so in rather a hurry.

Fortunately, my experience came in an altitude chamber at Langley Air Force Base, Va., as part of an FAA-sponsored physiological training program made available to pilots at locations around the country (see "FAA Physiological Training" sidebar). Had I been at the controls of an aircraft, I doubt I could have even comprehended a problem, much less resolved one.

High on Hypoxia

When we think of pressurization problems in an aircraft, we tend to focus on the dramatic rapid decompression scenario. Wham! The cockpit instantly fills with a dense fog, and an icy chill quickly settles in. Amid the cacophony of master caution warning horns excitedly announcing a problem, and the outrush of precious air, there's no doubt that a full-fledged emergency has erupted, and we know for a fact that the situation must be dealt with, and quickly.

The major concern in a loss of cabin pressure is the reduction in available oxygen, and the physiological effects it has on the processing of the human brain. While this condition is generally known as hypoxia, there are actually several varieties of hypoxia, each differentiated by the particular mechanism involved. And this is where the physiological training program at Langley AFB begins.

Our instructor, Air Force physiologist Lt. Katherine Baerwald, starts the discussion with a review of the basics of human cardiopulmonary circulation. As she explains, the process begins with ventilation of the lungs. Inhaled air is drawn into the deepest recesses of the lungs -- tiny sacs called alveoli -- where the exchange of gases occurs across a thin membrane separating the air space and blood. Carbon dioxide disassociates from the red blood cells and diffuses into the air space, replaced by life-giving oxygen.

The next phase in cardiopulmonary circulation is transport of the gases to and from the various parts of the body. Oxygenated blood leaves the lungs and flows to the heart, which pumps it through arteries and ever-smaller blood vessels until it reaches the capillaries that serve individual organs and cells. Here, the oxygen diffuses into the cells, and CO_2 diffuses into the blood. The CO_2-laden blood now makes its way back to the heart, and is pumped back to the lungs where the cycle begins anew.

The final phase is the utilization of the oxygen in the various tissues at the cellular level. Through a complex series of biochemical reactions, the oxygen molecules are broken down to release energy and combined with the carbon from carbohydrates and sugars to make CO_2.

As soon becomes obvious, interrupting the cardiopulmonary circulation at any point can result in hypoxia. When the air reaching the alveoli contains insufficient oxygen -- whether due to a mechanical system failure or improper transport of oxygen-rich air into the lungs -- the result is what is called "hypoxic hypoxia" or "altitude hypoxia."

Stagnant hypoxia occurs when the circulation of blood is interrupted. This can occur because the individual is subject to a high g-loading, due to restrictive clothing, or because of excessive tension in seat restraints.

When sufficient oxygen reaches the alveoli, but the oxygen-carrying capacity of the blood is compromised, we have what is called "hypemic hypoxia." Hypemic hypoxia can occur due to a number of conditions, such as anemia or abnormalities of the blood hemoglobin (the chemical oxygen carriers), the effects of various drugs or medications, or most commonly due to the presence of carbon monoxide, which binds to the blood hemoglobin with an affinity many times greater than does oxygen.

Finally, histoxic hypoxia occurs at the cellular level when toxins prevent or inhibit the proper metabolism of oxygen. Histoxic hypoxia is typically the result of alcohol, narcotics, or cyanide released in the combustion of various plastics and synthetic fabrics.

By far, the most common form of hypoxia in aviation is altitude hypoxia, caused by the reduced pressures of altitude. Although the air still contains roughly 20 percent oxygen, the partial pressure of oxygen in the lungs is insufficient to afford the diffusion of oxygen into the blood. However, it also becomes clear that other scenarios could readily induce hypoxia in pilots and passengers. The release of HAZMAT, ingestion of certain contaminants via the cabin pressurization system, overheating of components (such as wiring insulation) or an onboard fire could quickly result in histoxic hypoxia.

More Fizziology

Lack of oxygen isn't the only problem to confront a hapless pilot who finds himself suddenly thrust into thin air. These additional threats might not be as obvious as loss of consciousness, but they can be every bit as ominous.

Before venturing to 25,000 feet for our hypoxia demonstration, we spent half an hour breathing 100-percent oxygen at sea level. This precaution is designed to reduce the risk of another pressure-related malady: decompression sickness.

Decompression sickness occurs when pressure is decreased, allowing dissolved gases (primarily nitrogen) in the body to come out of solution and form bubbles, much the same way as bubbles form when we release the pressure from a can of soda. Pressure from these bubbles can cause severe pain, local restriction of circulation, and in severe cases, death. Symptoms of decompression sickness include pain in the joints, numbness and tingling of an arm or leg, partial paralysis, loss of speech or hearing, vertigo, visual disturbances such as blind spots in the visual field and the sensation of flashing or flickering lights, and rashes or itching of the skin. By prebreathing pure oxygen, nitrogen diffuses out of the body, reducing the risk of decompression sickness.

Yet another form of potentially serious discomfort comes from the expansion of gases trapped in various bodily locations -- namely, the ears and sinuses, the gastrointestinal tract and within teeth. Air trapped in the sinuses due to a cold or allergy may not cause a problem as the cabin altitude rises, but the pain can be unbearable when a rapid correction is made to decrease altitude and restore pressure. However, air trapped in dental work can cause excruciating symptoms as pressure decreases and the air expands. That bean burrito you grabbed for lunch might cause you some level of discomfort at nominal cabin altitudes, but the effects following a cabin depressurization could be truly gut-wrenching.

The Cold Facts

As surely as Charlie had to cope with freezing temperatures, the high-altitude flight environment poses a risk of cold exposure. High altitude and low temperature go hand in hand, so if a problem develops that leaves us without pressurization, we will most likely also be faced with the problem of cold temperatures. As Oscar Gibbs, a former Air Force physiologist, warns, "A decrease in body temperature due to cold exposure over time will result in performance decrements." According to Air Force sources, these performance decrements include an increase in decision time, errors of omission, and some degradation in visual acuity. Individuals will be slower to complete routine tasks, and mechanical mistakes will be more common.

The remedy for a loss of pressurization capability typically involves descent to a lower altitude, but as long-haul and over-water flights become more common, this option needs to be reexamined. Depending on fuel status, weather condition and other factors, a crew may be forced to maintain an uncomfortably cold altitude in order to reach an acceptable alternate. When this happens, crews will have to cope with the cold and can expect to face some of the performance decrements. To prepare for such a contingency, flight crews should dress appropriately and carry some form of emergency exposure protection garments.

Different Strokes

Clearly, the most immediate danger with a loss of cabin pressure is hypoxia, and the clues that hypoxia is at work come in a variety of objective and subjective signs and symptoms. When evaluating another individual, the objective symptoms include an increase in the rate or depth of breathing, poor muscle coordination, cyanosis (a bluish tinge of the lips or beneath the fingernails), mental confusion, poor judgment and a loss of ability to communicate. Subjective symptoms can include air hunger (feeling like you need more air), apprehension, headache, dizziness, fatigue, nausea, hot and cold flashes, blurred vision, tunnel vision, tingling and numbness. Some individuals may also experience euphoria or belligerence.

As Lt. Baerwald explains, "Individuals are different, and each will experience slightly different symptoms. But the symptoms stay the same for each individual." Not all individuals will experience all symptoms, but the symptoms an individual has will be the same each time they experience hypoxia. The primary purpose in completing the altitude chamber portion of the physiological training program is for pilots to learn to recognize their own personal symptoms.

Two of us were enrolled in the program the day I took the "chamber flight," which typically runs 1.5 to 2.5 hours, and our personal symptoms were distinctly different. My training partner, National Geographic science writer Mike Klesius, drew the short straw and was first to remove his oxygen mask at a chamber altitude of 25,000 feet. Within a couple of minutes, cyanosis was evident -- a bluish tinge beneath his fingernails. He seemed relaxed, and calmly reported his symptoms, but I couldn't help noticing the difficulty he had in reattaching his oxygen mask at the end of the demonstration -- a task that had presented no difficulty at sea level.

"I remember the initial symptom as a mildly annoying shortness of breath," says Klesius. "Not panting so much as the impression of a foot on my chest, or an inability to get a deep and satisfying gulp of air. Then some dizziness and a sense of relaxation bordering on apathy, very much like a fresh alcohol buzz. My vision didn't really blur, but the room seemed brighter, as if someone were gradually turning up the light. My feet grew cold, which has been chronicled by Everest climbers, including Hillary himself."

In contrast, when I first removed the oxygen mask, I felt a wave of dizziness that quickly subsided. Next was the mental confusion, manifested in an inability to comprehend simple instructions. My vision became somewhat blurred, and I had the distinct sensation of being flushed.

Although the symptoms an individual experiences will be the same from one altitude exposure to the next, the time and altitude at which these symptoms manifest will likely vary. One of the primary factors influencing the onset of symptoms is the rate at which the pressure changes. In a gradual depressurization, the onset of symptoms may be delayed. In a rapid depressurization, symptoms will occur much more quickly.

One of the primary measures of performance degradation due to hypoxia is the Time of Useful Consciousness (TUC). This represents the time that an average individual has sufficient mental capacity to take the proper corrective and protective actions, such as donning an oxygen mask or completing a checklist. An important side note is that the TUC can be dramatically reduced if the drop in pressure is rapid. "The actual TUCs can be 30 to 50 percent less in a rapid decompression," notes Baerwald.

In fact, Dr. Tom Yasuhara, an Associate Aeromedical Advisor with the Air Line Pilots Association (ALPA) Aeromedical Office in Aurora, Colo., offers slightly more conservative TUC values consistent with rapid decompression (RD). As he notes in the Aeromedical Update, "The dramatic hypoxic effects associated with an RD reflect the sudden outward flow of oxygen from the tissues when sudden exposure to a lower atmospheric pressure occurs." The bottom line is that in an RD at high altitude, pilots have precious little time to take action. If the mask isn't on with oxygen flowing in short order, the situation will surely go from bad to worse.

Other factors influencing the onset of hypoxia symptoms include nutritional status, fatigue and level of physical activity. Self-imposed stresses such as the use of tobacco, alcohol consumption and poor diet can also reduce an individual's tolerance to decreased oxygen levels.

Epilogue

While the chances of an unscheduled cabin decompression might be relatively small on any given flight, the opportunity to experience the symptoms of hypoxia firsthand offers important insights into the potential problems of high-altitude flight, and reinforces the need to take appropriate precautions. When push comes to shove, most of us prefer the comfort and safety of our pressurized cabins to the harsh environment of high altitude. And when the pressure's off, we might fare better if we're in Charlie's shoes -- thoroughly prepared to cope with the realities of the outside world. **B/CA**

FAA PHYSIOLOGICAL TRAINING

FAA-sponsored physiological training programs are available to pilots at numerous locations across the United States. The program consists of approximately four to five hours of ground instruction covering a variety of topics including high-altitude physiology, situational awareness, vision and visual illusions, spatial disorientation, and other factors affecting human performance (noise and vibration, fatigue, thermal stress, acceleration). Students learn how to properly test and configure oxygen breathing systems typical of military aircraft, and then undergo the high-altitude chamber tests to experience the effects of hypoxia on a firsthand basis.

The program is offered free of charge at the FAA Mike Monroney Aeronautical Center, Civil Aerospace Medical Institute (CAMI) in Oklahoma City. It is also offered for a $50 fee at 14 Air Force bases around the country, as well as at the U.S. Army's Fort Rucker, Ala. All courses are scheduled through the FAA. To enroll in the program, contact the FAA in Oklahoma City at (405) 954-6212.

DECOMPRESSION -- THREAT OR THEORY? A PROBLEM UNMASKED

When asked how regularly he or his copilot donned an oxygen mask when operating above FL 410, one Global Express pilot casually admitted, "Never." And even though that omission is in direct violation of the FARs, it's probably (there are no statistics on this) not uncommon behavior.

The preference for naked faces at altitude appears to stem from three separate issues. First, even the most modern oxygen masks are notoriously uncomfortable, and the idea of wearing one for perhaps hours is utterly off-putting. Second, the sight of a pilot wearing a mask can be unsettling to the often apprehensive, unmasked passengers in back. Third, and perhaps most important, is the perception by flight crews that the risks of decompression are so mitigated through robust aircraft design, redundant systems and highly reliable warning systems, that depressurizations are a thing of the past. Yes, there is the occasional event such as the Payne Stewart crash, but some believe such failures are so rare that the regulations on donning masks are obsolete and need to be revised.

However, not everyone is convinced that the risks have been obviated. At the conference of the Aviation Medical Society of Australia and New Zealand (AMSANZ) in September 2000, Dr. Rob Griffiths, academic coordinator of the Aviation Medicine Program at the Wellington School of Medicine, presented data suggesting that there remains considerable danger of cabin decompression.

Griffiths said that 40 to 50 rapid decompressions are reported annually on a worldwide basis. Further, he suggested that estimates of one rapid decompression per 50,000 flying hours appears to be an underreported figure, based on cabin pressurization failure rates in Australia. Even at that, a professional pilot who accumulates between 10,000 and 20,000 hours of flight time would have a one- to two-in-five chance of experiencing a rapid decompression sometime in his or her career.

While the data suggest that incidents of cabin depressurization are generally transient and readily resolved, Griffiths also pointed out that a significant number of the incidents occur at altitudes where such an event could pose a serious risk. Data from the NASA Aviation Safety Reporting System (ASRS) and Australian Transport Safety Bureau (ATSB) indicate that 4 percent of the incidents occur at FL 400 or higher. ASRS data indicate that 69 percent of the reported incidents occur at FL 300 or higher, whereas the ATSB reports less than half that (33 percent) at FL 300 or higher. ASRS data also express that in 6 percent of the incidents, the maximum cabin altitude reported was 20,000 feet or higher.

ASRS data also include revealing statistics regarding depressurization rates. The data indicate that in 30 percent of the reported incidents, the depressurization is rapid (more than 2,000 feet per minute). Another 30 percent are reported as moderate (500 to 2,000 feet/minute), 21 percent slow (less than 500 feet/minute) and 9 percent insidious (very slow).

While the rapid decompression scenario may be more dramatic, and imposes a reduced time of useful consciousness, a slow decompression may in fact be more problematic. Without the bells, whistles, rushing air and fog, there might be very few clues to indicate that we have a problem. Considering the insidious symptoms of hypoxia itself, we might not realize we have a problem until it's too late.

One commonly held myth is that outflow valves in aircraft are the most common cause of depressurization, but reported data refute that theory. According to Griffiths' report, both ASRS and ATSB data attribute one-third of the incidents to failure or malfunction of the pressurization controllers. Next on the list is a mechanical failure at the pressurization source -- either bleed air or air-conditioning pacs -- resulting in 15 percent (ATSB data) to 29 percent (ASRS data) of the incidents. Structural failures account for 12 percent (ATSB data) to 21 percent (ASRS data) of the reported incidents. Operator error was the culprit in only 5 percent of the ASRS reports and 2 percent of the ATSB reports.

As for malfunctioning outflow valves, ATSB data indicate that they're the culprit in only one in five cabin decompression incidents.

So despite durable design and systems, aircraft unplanned depressurizations continue, with a rapid decompression besetting some unwitting, startled crew somewhere every couple of days. Pilots should be concerned and take appropriate precautions when flying at altitude.

HYPOXIA AND NIGHT VISION

Visual disturbance is among the common symptoms associated with hypoxia, but the effects are most notable in dim lighting. As part of the FAA physiological training program, pilots get to experience firsthand the degradation of night vision that accompanies hypoxia.

Our test was conducted at a chamber altitude of 18,000 feet. We were instructed to remove our oxygen masks, and make observations regarding an eye chart, color chart and a sectional aeronautical chart. After a few minutes, the lights in the chamber were dimmed, and we were asked to make the same observations.

Once the lights were dimmed, only yellow and orange were visible on the color chart, and the eye chart was completely illegible. I also found it impossible to read the sectional chart. After a few minutes, we were instructed to resume wearing our oxygen masks. Within a brief time, I could read the eye chart, distinguish colors and read the sectional chart.

The take-home message is that night vision adaptation (or lack thereof) is a clear indication of hypoxia, and should be included in the list of symptoms indicating a problem with aircraft pressurization. What's more, a lack of night vision constitutes a serious safety hazard for any flight crew attempting to operate without oxygen masks or cabin pressurization at high altitudes.

Reprinted from the April 2003 issue of *Business & Commercial Aviation* magazine