The Safety Aspects of Wave Flight

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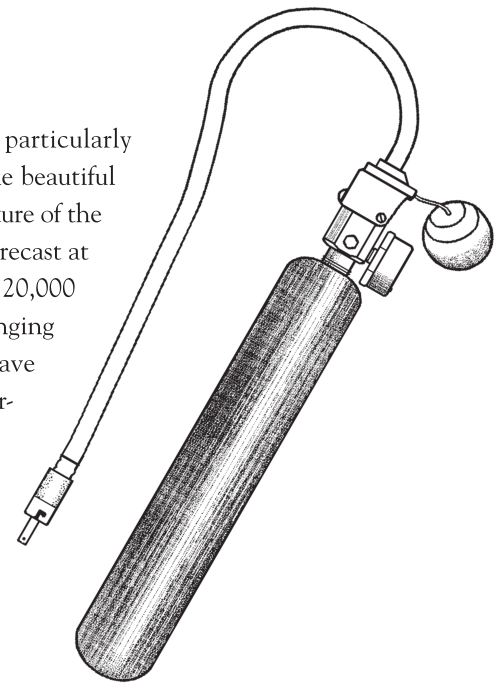
The human body is not designed to operate above 16,000 feet for any length of time, and altitudes above about 25,000 feet should be considered hazardous and unhealthy territory for the unpressurized pilot.

There are many physiological effects of flight at altitude which must be understood and compensated for in order for the pilot to be safe.

This paper on the risks and physiology of high altitude flight is part of *"Stalking the Mountain Wave",* vol 2 by Ursula Wiese.

1992 – Bailed out by the bailout bottle

Jay Poscente



THE FAMOUS Cowley wave was not particularly strong this day, nor was it marked by the beautiful lenticular clouds that often help form a visual picture of the smooth bands of lift. High altitude winds were forecast at over 100 mph and a 40 to 50 degree windshift at 20,000 feet further complicated the climb. The challenging but erratic two hour ascent in rotor and broken wave generated a barogram that looked more like a thermal flight than that of a wave climb.

The lift topped out at about 25,000 feet ruling out any record attempts, so I decided a bit of wave cross-country might be fun. I had neglected monitoring my oxygen pressure during the difficult last half of the climb as my gauge is mounted inconveniently on the regulator behind my head. I looked back to check the pressure and my heart stopped. "ZERO! ... DOES THAT GAUGE SAY ZERO?!" Three panicky breaths later, the bottle was completely empty, the blinker stopped blinking, and my mask was suffocating me. Anxious to breathe, I pulled the mask from my face. The next nine minutes seemed more like an hour.

In a hurry to descend, I initiated a quick 180 degree turn towards the sinking side of the wave but found the controls frozen nearly solid by the –35C temperature. The resulting high speed uncoordinated turn was quite unnerving. "Don't panic. Breathe deeply and slowly," I told myself. "Dive in the lee of the wave, get the oxygen mask back on your face, then activate your bailout bottle," (a tiny emergency oxygen bottle designed for military pilots so they can bailout at high altitudes).

Unfortunately, maneuvering into the descending side of an invisible wave with stiff controls while trying to maintain constant speed in the steepest dive I had ever experienced proved challenging. Add the complication of trying to free and lower a frozen landing gear (to increase drag) while holding open powerful dive brakes that want to close at high speed, and I found myself postponing the task of replacing my oxygen mask. I was already down to 22,000 feet and thought, "perhaps diving at this rate I will have enough time to make it down without emergency oxygen."

Then, hypoxia set in.

It did not creep up on me with the "subtle feeling of wellbeing" I had read about. It hit me like a bag of hammers and it was frightening. Heart pounding, ears ringing, tunnel vision, head spinning and tingling all hit at once and hit hard. I was flying at the edge of my frozen bird's performance envelope and felt I could pass out at any moment.

I fumbled with my oxygen mask and banged my knuckles as I reached to activate the bailout bottle strapped to my thigh. "Wonderful," I thought. "There go my motor skills!" Craving a rush of oxygen to clear my head, I yanked repeatedly on the little bottle's activation cable, but nothing happened. My mask was suffocating me again. It was like trying to draw a breath from an empty pop bottle. I moved my mask off to the side of my face and gasped at the rarefied air. A sickening feeling of helplessness welled over me. I was losing consciousness and there were no more options. All I could do was dive at the Livingstone Range and wait. Time stood still.

I vaguely remember noticing the airspeed approach 100 knots (somewhere near redline for this altitude) and thought, "Slow it down or you will break the glider." I must have flown through a band of moist air because a layer of frost formed on the canopy and wings. I remember peering through the ice streaked canopy to see how close to the ground I was getting. I also remember the deep feeling of disappointment at seeing the mountain peaks still two miles below.

Now resigned to my predicament, a sense of calm settled in. I felt numb, like I was dreaming, and watched curiously as the tunnel vision tightened and as colours faded to greys. For lack of any other options, I gave the bailout bottle another try. Expecting my oxygen mask to suffocate me again, I took a deep breath and held it before fumbling with my mask and bailout bottle. As I was holding my breath, mask in place, I noticed pressure building in the mask. Fear turned to elation!

I tried desperately to get a deep breath, but it was like trying to breathe through a tiny straw. Again, I yanked at the activation cable thinking it was only partially open, but there was still no rush of oxygen, just enough to get a mouthful every few seconds. Enough, I suppose, to stay conscious for the seven to ten minutes that these 22 cubic inch bottles are designed to deliver.

With my heart pounding, trying to match my breathing to the torturously slow rate of oxygen flow was nearly impossible. But the pure oxygen quickly cleared the harshest symptoms of the hypoxia. Thoughts began racing through my mind. I remember suddenly realizing just how very dizzy and cold I was. I got angry with myself for having neglected my oxygen pressure gauge on the way up, but was relieved to realize that at this point, I was probably going to make it back down, in one piece.

Again, I caught the airspeed approaching redline, only this time I was approaching a nasty looking rotor cloud! Sobered by images of my frozen fibreglass sailplane breaking to pieces in violent rotor at 100+ knots, I pulled out of the dive as gently as I could. "I've made it," I thought! "I can wait at this altitude for my ship and brains to thaw out."

It took me a couple of minutes to realize, however, that I was still at thirteen thousand feet, bailout bottle now empty, and still starving for oxygen. It was a quick dive to ten thousand feet. Mercifully, I was spared any dealings with rotor and was able to establish a holding pattern in light wave lift for about twenty minutes while my glider and I thawed slowly at +2°C. The phrase, "You can breathe easier now", took on a whole new meaning!

Everything seemed to be going fine until I found myself snapping out of a daydream in strong sink. I wasn't sure if I had recuperated enough to attempt a high wind landing yet but I was sure that I was in heavy sink and would definitely be on the ground somewhere soon, ready or not.

I headed for the Cowley airstrip, reviewing my circuit procedures and landing checks over and over, concentrating heavily all the way in. Despite the high winds, it may have been one of my best circuits ever and I was so happy to touch down safely that I forgot who was driving and promptly botched the roll out! I sat motionless in the glider for awhile savouring the profound feeling of relief and contemplating how fortunate I was to be there with no damage to plane or pilot.

I am not proud of this avoidable adventure. It was the result of my neglecting an instrument important to the safety of the flight. However, research and the luxury of hindsight have allowed me to make a few safety related observations that should be shared with other high fliers.

Observations:

- SCUBA training taught me that the deeper you go underwater (increasing pressure), the more air you use with each breath. I had assumed that the higher you fly (decreasing pressure), the less bottled oxygen you would use with each breath. Wrong! In fact, the higher you fly with a diluter demand regulator, the more oxygen you draw from your tank with each breath. Breathing through an oxygen mask at 10,000 feet, your regulator mixes mostly outside air with a small amount of bottled oxygen. By 32,000 feet, most regulators are automatically supplying 100% bottled oxygen to your mask.

I had been monitoring the oxygen pressure during the early stages of this climb and based on the slow rate of oxygen depletion at moderate altitudes, I had assumed there was at least an hour more capacity than turned out to be the case at higher altitudes.

- There are those who would say I was not extremely high at 25,000 feet. The chart says you should have up to five minutes of "Time of Useful Consciousness" (TUC) without supplemental oxygen at this altitude. But what if you don't realize that your oxygen supply has been deteriorating for awhile? I believe this is what happened on my flight. I had less than one minute from the time I discovered the trouble until I developed substantial physiological difficulties.

"Blinkers" (oxygen flow indicators) blink shut while oxygen is flowing through the regulator. My blinker was trying to tell me that something was wrong for about 15 minutes before I ran completely out of oxygen. When the pressure got low, my blinker only closed briefly at the beginning of each breath rather than its usual practise of staying closed throughout each inhalation. I probably was not getting enough oxygen this whole time and was becoming increasingly hypoxic without realizing it.

I failed to notice three signs of deteriorating judgement during the last 15 minutes of my oxygen supply. I saw the blinker's subtle change in behaviour but for some reason I shrugged it off without further investigation. Then, I decided to fly cross-country despite ridiculously high winds, no flight plan and no retrieve crew. Finally, I have no idea why I took off my mask when my oxygen ran out. It would have made more sense to immediately activate the bailout bottle. These events all occurred prior to my having noticed any sign of hypoxia.

- Descending is a rather poor emergency procedure for high altitude oxygen system failures. During an emergency descent, you are not recovering during the dive, your condition continues to deteriorate, albeit at a decreasing rate until you are below 10,000 feet. Above 20,000 the problem compounds rapidly. The higher you are when the problem occurs, the less time of useful consciousness you have and the farther you have to dive, your hypoxic condition worsening the whole time you are above 10,000 feet.

Furthermore, your rate of descent is a big unknown. Will you be able to locate and stay in the lee of an invisible wave once hypoxic and diving? You could be diving in lift. I was flying a Mini-Nimbus which has extremely effective dive brakes. My barograph recorded this very steep descent at a fairly steady 2000 feet per minute. I thought I was in the lee of the wave but will never know. The 50 degree windshear somewhere around 20,000 feet confused the shape of the wave and the vario is useless diving at high rates.

After I discovered the problem and after the dive was established, it took an additional six minutes to descend to 13,000 feet. What if I did not have a bailout bottle? What if I had been at 28,000 feet where a healthy military pilot has about 90 seconds before passing out without supplemental oxygen? A lot of pilots at this year's wave camp achieved 28,000 feet and higher.

How fast can your glider descend? What is its redline at various high altitudes with dive brakes fully open? From what maximum altitude can you survive an emergency descent without oxygen assuming what vertical speed? At what altitude will one bailout bottle not have enough capacity for you to survive the descent? At what altitude should you abandon ship and free fall to a safe altitude and will your face and eyes be protected against terminal velocity at –40C?

- Prior to this episode, I had encountered a rather widespread cavalier attitude towards bailout bottles. The day after my misadventure, I was happy to see considerably more attention being given to these convenient little life savers on the Cowley flightline. I hope this article will inspire a few more pilots to carry bailout bottles on all wave flights and to thoroughly understand how they work.
- When you use an instrument only a few flights a year, as is often the case with oxygen instruments, you have to make a conscious effort to alter your normal instrument scanning habits.
- There is no rush of oxygen when a bailout bottle is activated. About a 20 pound tug on the green ball activates a low volume free flow of oxygen that decreases in both volume and pressure over the seven to ten minutes it takes to deplete the bottle. Try breathing through a one-eighth inch drinking straw or one of those coffee stir sticks that look like a squished straw for a few minutes to get the idea.
- My experience with hypoxia was not what I expected. Since everyone reacts differently, anyone intending to fly wave should seriously consider taking an altitude chamber ride. Your local department of aviation medicine can steer you in the right direction. Hypoxia, like a low level spin, is best recognized in its incipient stages.

1995 – How can you talk and breathe at the same time?

Todd Benko

… I HAVE THE DIAMOND in sight with 4 knots lift and it seems only inches remain to be gained. Soon reaching 27,000 feet, I have it. I decide to take this elevator to the top floor which means calling for a clearance above 28,000 feet. I look around the cockpit and locate my little piece of paper that has the appropriate frequencies written on it. Now, just how do I use the handheld radio through the oxygen mask? I try a transmission with the mask on. No way. I remove my glove and mask and broadcast. "Edmonton Centre, this is glider X–ray Quebec Lima." No reply. I wait a few seconds while taking a couple of breaths from the mask. I try again, still with no reply. Not wanting to risk hypoxia by having the mask off too long, I decide to change to the backup frequency. Finally making contact with the controller, he requests I change back to the primary frequency. Still no contact is made, but I can hear other aircraft communicating on frequency.

As my altimeter steadily approaches FL280, I ask any aircraft reading my transmission to act as a relay, getting no response from them either. Finally, as I level off at 28,000 I am able to re-establish contact with the controller on the backup frequency and ask to go higher. He responds, "Do you have a transponder?"

My little cockpit comprises a single seat, no heat, no power, no motor, bottled oxygen, a handheld radio and enough clothing to venture out into a –40 degree blizzard. I reply, "Negative". A somewhat pregnant pause occurs, undoubtedly due to a miniconference developing around the radar scopes. Finally the controller returns and clears me to no higher than flight level 330. I read back my clearance, "No higher than flight level 330", and I put the radio down.

It is only now that I realize something has changed. The sound of the air over and around the canopy appears different. The sharpness of the hissing is almost gone and is getting more muffled. I quickly realize that hypoxia might be setting in. I put on my oxygen mask and select 100% oxygen. I also realize that the outer limits of my peripheral vision seemed to be fuzzy, however this clears up within thirty seconds on oxygen. A couple of minutes later my hearing returns to normal and I select the oxygen to normal operation. All the pauses with the controller caused me to lose track of how long I was off the mask. When I tighten the mask, I find that the ear muffs in the cloth helmet prevent me from clearly hearing anything on the radio. Later proving to be a less than ideal decision, I elect to turn the radio off in case the battery is getting weak. I did not remember that I had to remain in radio contact with the controller at all times above FL280.

I put the glove back on my freezing hand and eventually top out at 28,700 feet, and I inform the controller as I drop below flight level 280. The controller questions if I heard his calls. I am sharply chastised after I tell him I had turned the radio off. I sheepishly apologize for my sin and proceed with my descent. Finally landing back at the field, I was exhilarated! Only as I sat back later did I slowly realize what I had endured, learned and achieved.

A trip to Cowley – worst case scenario

Rick Zabrodski, MD

YOUR LONG TIME FRIEND who lives on the west coast near Victoria is coming out to fly your glider at the summer camp at Cowley at your invitation. He has never flown at Cowley before and never flown any higher than 12,500 asl.

"Big Bob" when he arrives is bigger than when you saw him last. You note when you meet him at the airport that he is still smoking two packs a day and when you mention this he tells you that you sound like his doctor who sees him regularly during the winter months when Bob gets recurrent bronchitis every 6 weeks. In fact Bob is just recovering from such an infection and has cut down to one pack a day! Being the tough guy he always has been though, this didn't stop him from donating a pint of blood yesterday at the donor clinic held at his office.

You drive down to Cowley and, because its dry and summer, Big Bob's hay fever starts to act up. He's sneezing and getting red eyes so he picks up some antihistamines when you stop for the beer. Both of you have a great evening together recalling past adventures and near misses as aviators and after polishing off the 12 beers go to bed at 3 am.

You both wake at 7 am with the tent flapping in the wind. A front has come in and there are lennies over Centre Peak in August! This is Bob's big opportunity to get his first Diamond! No time for breakfast (just three quick cigarettes), you quickly untether the glider and Bob climbs in. It's warm outside and summer so he is wearing a cotton shirt and shorts. Your bail-out bottle is at home (you forgot it), but you are not worried because you have never needed it anyway. You tell Bob to keep an eye on the blinker and to worry if it stops blinking.

As Bob takes off behind the towplane your partner comes up to you and asks if you filled up the oxygen because there was only 500 pounds left last night after his flight. You hadn't noticed this because the gauge is mounted just behind the headrest and was obscured by the barograph that Bob had installed. You try to call Bob on the radio but he has forgotten to turn it on, probably because your mask doesn't have a microphone in it so he wasn't planning on talking to anybody anyway.

The ASC safety officer who just found out that your friend was flying today comes over to insure that Bob's medical and licence are current. Are they? Well, at least you explained the Livingstone Block procedures including altimeter adjustments and use of airspace, didn't you? I guess not, because another glider who is holding at flight level 280 because of upper commercial traffic just saw your glider go up beside him, nearly hitting him as if he wasn't there! Now he reports that your glider is 4000 feet higher now and still climbing despite –40°C temperatures.

Bob might very well not get back to the ground in one piece. If someone had given HIM a Daily Inspection, he would surely have been grounded on medical factors alone.

Hypoxia and the respiratory process

Rick Zabrodski, MD

RESPIRATION is the process by which living organisms exchange gases with the environment. In human beings, this means providing oxygen and removing carbon dioxide from the cells of the body. For this to occur we require sufficient oxygen concentration to be brought to the lungs via ventilation (breathing). Once at the lung tissue level these gases must diffuse across a membrane and then be transported via blood (hemoglobin) and diffuse again to the tissues. Finally, the oxygen must be utilized within the cell to produce the energy necessary to sustain life.

Hypoxia occurs when one or several steps just mentioned are disrupted to the point when oxygen deficiency occurs at the cellular level. *Brain cells with their uniquely high oxygen demand are most susceptible to low oxygen pressure*. Hypoxia can be classified into four types:

Hypoxic hypoxia — This is a deficiency in oxygen at the lung tissue level due to a decrease in oxygen partial pressure (altitude induced hypoxia) or a decrease in effective gas exchange in the lung (eg. collapse of one lung).

Hypemic hypoxia — This can occur even with normal lung function and occurs when the transport of oxygen by hemoglobin is impaired. This occurs with anemia (decreased hemoglobin) or impairment of its function by carbon monoxide. CO levels are 6 to 7 times higher in smokers. Three cigarettes in 30 minutes puts your 'sea level' at 8000 feet and can seriously impair night vision.

Stagnant hypoxia — This is any condition causing a reduction in blood flow, especially to the brain. Clothing that is too tight, 'g' forces, changes in body posture, extreme environmental temperatures as well as certain medical conditions and drugs can all lead to this problem.

Histotoxic hypoxia — This refers to metabolic disorders that interfere with the cells ability to utilize oxygen. Cyanide works at this level as do many toxins. However drugs can also have a significant impact including our old friend, ethyl alcohol.

It must be emphasized that these effects are additive. Thus an out of shape, overweight, tired, smoking pilot who had a few beers with his antihistamine last night who goes flying without breakfast after donating blood may find himself suffering from hypoxia much sooner than what we would expect from a young, healthy, well rested and well fed pilot on whom the data for hypoxia has been derived.

Stages of Hypoxia

Stage	Altitude (ft) breathing air	Altitude (ft) breathing 100% O_2
Indifferent	0–10,000	34,000–39,000
Compensatory	10,000–15,000	39,000–42,500
Disturbance	15,000–20,000	42,500–45,000
Critical	20,000–25,000	45,000–46,000

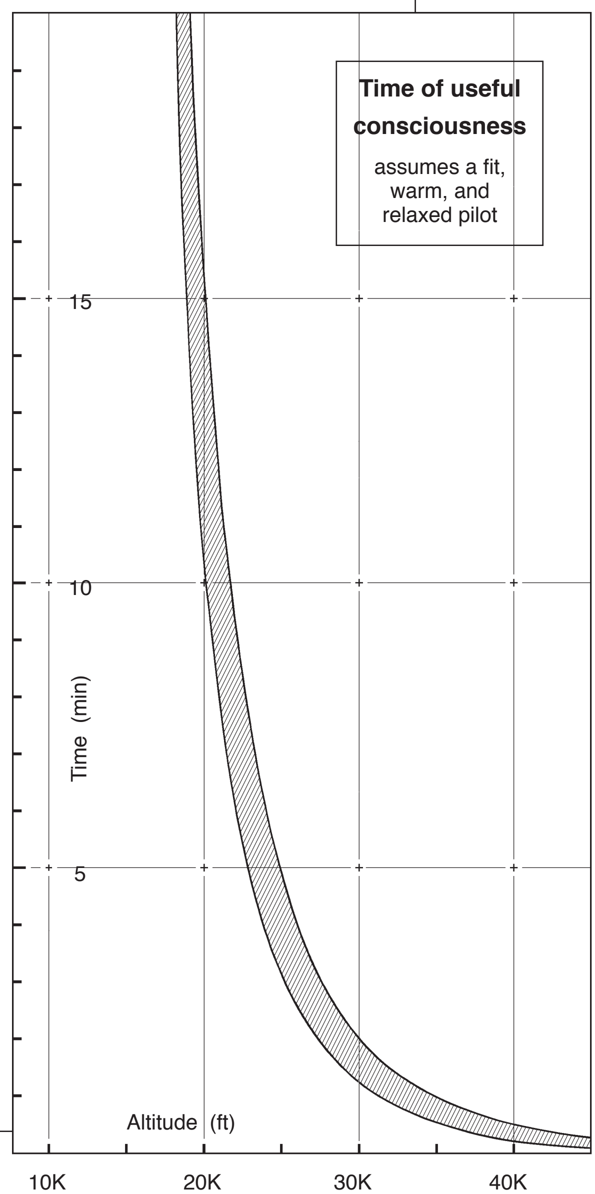
Use of a tightly fitting mask delivering 30 mm Hg pressure and 100% oxygen will give a safe altitude limit of 42,500 feet corresponding to the indifferent/compensatory stage. Pressures greater than 30 mm Hg are not tolerated unless a counterpressure garment is worn.

Indifferent 10-30% reduction in visual sensitivity. Slight increase in respiratory and heart rate with impaired performance of new tasks.

Compensatory More pronounced change in respiration and heart rate provide some protection against hypoxia for a period of time. Drowsiness, decreased judgement and memory occur. Difficulty with discrete motor movements.

Disturbance Within 30 minutes symptoms such as air hunger, headache, somnolence, dizziness, euphoria and fatigue may develop. Thinking becomes slow and unreliable, memory faulty, and motor performance is severely impaired. Loss of peripheral field vision occurs (tunnel vision).

Critical Mental confusion within minutes followed by incapacitation with loss of consciousness, followed rapidly by death.



Guidelines for the Prevention of Hypoxia in High Altitude Flight

If in doubt, go to 100% oxygen — still in doubt? — use your bailout bottle!

Know your symptoms. Ideally, experience hypoxia in an altitude chamber to understand how you react. A possible alternative might be a dual flight in wave with an instructor observing your flying while off oxygen.

Know your body. If you smoke, quit. Preferably no alcohol within 48 hours. Don't fly if you are sick or on medication (including nonprescription drugs) without your doctor's okay. Get a good rest and eat something before flying.

Know your glider and equipment. Make sure it all works. Consider a warning or backup system and understand the limitations of your oxygen system. They are not all the same!

Know your environment. You must dress prepared for the cold but also be comfortable in clothes that are not too tight and allow the normal operation of controls in an already cramped cockpit. How easy and how fast could you bail out if you had a midair collision at 20,000 feet?

Know the limits. A conservative pilot not worried about breaking the world record should fly assuming his oxygen system will fail and that his altimeter may be underestimating his real altitude by as much as 2000 feet. With this in mind, assuming rapid recognition of a malfunction and immediate descent, I would recommend flights not to exceed 28,000 feet to insure a safe return.

Know the very real risks. If break records you must, then consider doing it together with another pilot, in two ships or, even better, in a two-seater. Carry two completely independent oxygen systems and a bailout bottle. They will both be the positive pressure diluter demand type systems in good shape. Shave your beard and moustache and make sure your mask gives a good seal. This means a tight fit so that you must make an effort to exhale. A radio that works at –40° is essential and you need a microphone in your mask. Having radio contact with somebody monitoring your progress would be desirable. You should have some short mental or motor task to perform at set altitudes and be ready to abort the attempt if you experience any difficulty performing these tasks. Finally, anything beyond 44,000 feet will be courting your early demise. If you really need to go that high, get a space suit!

Hypoxic signs and symptoms are enhanced by several factors: altitude, time spent at altitude, rapid rate of ascent (or loss of oxygen supply), extreme environmental temperature, and self–imposed stresses such as fatigue, alcohol consumption, tobacco products, certain medications and inadequate nutrition.

A lecture on breathing

Don Clarke, MD
from *free flight*, 1974

When he wrote this article, Don Clarke was a glider pilot and professor of Physiology at the University of Toronto.

FOR SOARING PILOTS, hypoxia is something to be avoided. Put on your mask, watch the blinker, and that's about all there is to it! A knowledge of how to avoid hypoxia is all we usually need, however, there are interesting facets to the way that the body gets oxygen, and I would like to discuss the process of oxygen delivery to the tissues of the body.

Why do we need oxygen? The oxidation of food yields energy for muscular action, for nerve and brain activity, glandular secretion, growth, maintenance of body temperature, and so forth. This oxidation process must take place within the cells of the body, and in order to do this, adequate oxygen must be delivered to, and used by, the cells. If these processes of delivery and utilization do not take place, then the tissues of the body, and especially the brain, cease to function. The two processes of delivery and utilization must be kept in mind; later I will return to a consideration of the latter. Meanwhile, let us deal with the process of delivery.

The first step must be to get the air into the lungs. Air passes from the nose or the mouth into the trachea, and thence through branches (the bronchi) into microscopic sacs (the alveoli) and from the alveoli into the blood stream. Normally the lungs are expanded and held against the interior of the chest wall by forces of surface tension. Note that they are not attached to the chest wall by tissue structures. As we inhale, the chest wall moves upward and outward, the diaphragm moves down, the lung tissues follow this movement and in the course of expansion cause a drop in pressure inside the lung. Atmospheric air moves into this low pressure region. When we exhale, the weight of the rib cage, some muscular forces, and the natural elastic tendency of the lung tissues to collapse, decreases the volume of the chest cavity and air is forced out. The muscular motions are under nervous control influenced by a variety of factors, such as the concentration of oxygen and carbon dioxide in the inspired air, voluntary effort, pain, excitement, fear, etc. Normally we breath in and out about a half litre of air. With a maximum effort of inspiration and expiration, we can move about 4 to 5 litres of air in and out of the lungs with each breath. This extra capacity is used during exercise, or perhaps in special situations, such as coughing.

The whole process of delivery must result in supplying the interior tissues of the body with adequate oxygen. It turns out that one measure of adequacy is the partial pressure of the oxygen at the tissues. This partial pressure of oxygen should be 100 mm of mercury (Hg). If it is less than this, the possibility of hypoxia exists. The term "partial pressure" refers to the pressure exerted by a particular gas in a mixture of gases. For a given total pressure of a gaseous mixture, the lower the percentage of a given gas in the mixtures, the lower will be its partial pressure.

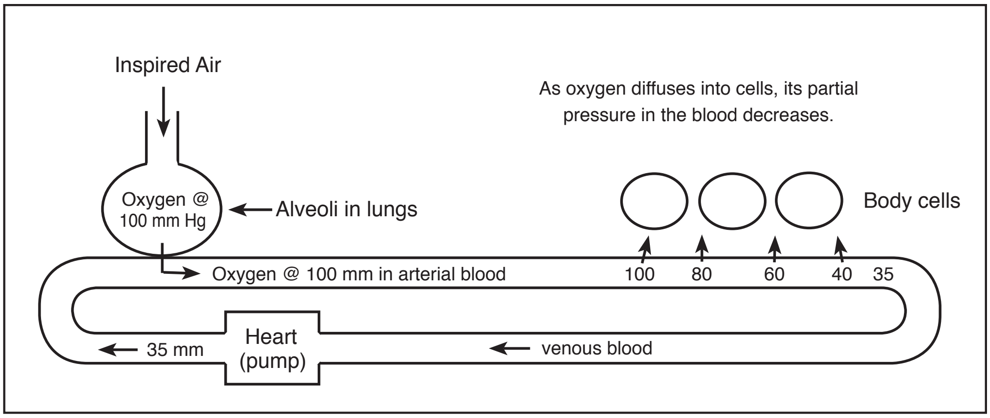
Obviously, to prevent hypoxia the air we inhale must have a sufficiently high partial pressure of oxygen. The partial pressure of oxygen at sea level in a normal atmosphere is 760 x 21% = about 160 mm Hg. When we inhale, some of the oxygen and nitrogen molecules are "displaced" by excess carbon dioxide and the water vapour in the saturated atmosphere of the lungs; as a result, the partial pressure of oxygen in the lungs is reduced to about 100 mm Hg. Rapid equilibrium takes place in the lungs between the partial pressures of the gases in the lungs and the partial pressures of gases in solution in the blood leaving the lungs. Oxygen moves from the alveoli into the blood. Carbon dioxide moves from the blood into the lungs for subsequent removal.

In any situation in which the partial pressure of oxygen in the gases inhaled is less than 160 mm Hg, there will be a reduced partial pressure of the oxygen in the blood leaving the lungs. Such a condition exists when we soar to high altitudes. The composition of the air we breathe is the same as at sea level, but there is a gradual reduction in the partial pressure of the oxygen in the lungs and thus in the blood stream. To some extent we can counter this by increasing the concentration and thus the partial pressure of the oxygen in the inspired air, but notice that a limit is reached here too. In anything but a pressure demand system, oxygen delivered to a face mask can never be delivered at more than the pressure of the surrounding atmosphere. This means that at about 34,000 feet 100% oxygen must be breathed. So if we fly higher, we are risking hypoxia. Note that simply breathing more deeply does not alter the partial pressure of oxygen, so it accomplishes very little (except perhaps to cause hyperventilation).

Bearing in mind that the usual volume of each breath is about half a litre, let us consider a rather artificial and extreme situation. Imagine yourself breathing in and out of a tube of 0.5 litre volume, with one end attached to your nose and the other end open to the air. Obviously the act of breathing will just move a "slug" of air back and forth in the tube. Neglecting the very small amount of mixing, no new air will be introduced and you will suffocate, even though the act of breathing is entirely unrestricted. The region in which no exchange of gases takes place, or "dead space", has been increased in this simple experiment. On more practical terms, we note that the design of face masks and breathing systems must take account of any increase in dead space and mask leaks which are introduced by the system to ensure that normal breathing is maintained. (It is for this reason that oxygen systems deliver 100% oxygen at about 32,000 rather than 34,000 feet.)

All of the above comments have referred to the process of getting oxygen into the lungs, where it can contact the blood stream. Next I will deal with the carriage of oxygen by the blood stream to the tissues.

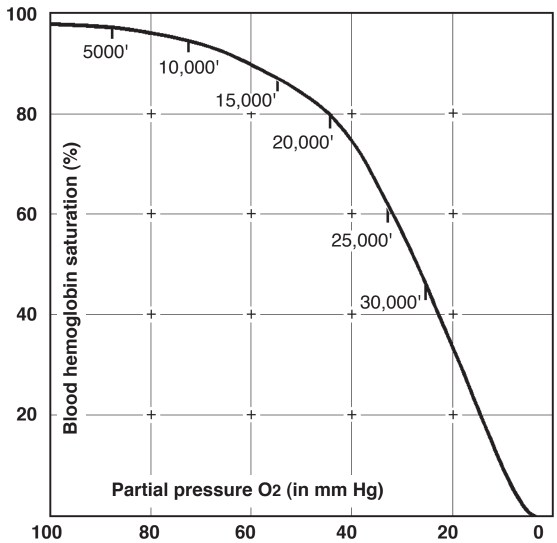
The alveolar sacs are so constructed that normally the blood in the vessels is separated from the air by a very thin membrane, and thus oxygen can diffuse rapidly from the alveoli into the blood. Now a gas in solution in a liquid may be shown to have a partial pressure, just as if it were in a mixture of gases. This partial pressure may be looked upon as a measure of the tendency of the gas molecules to escape from the liquid. The oxygen in the alveoli diffuses into the blood arriving at the alveoli until a near equilibrium condition is reached, ie. the partial pressure of the oxygen in the blood leaving the lungs is about the same as that in



the gas in the alveoli, or about 95–100 mm Hg. As the blood circulates to the tissues which lack oxygen, the gas diffuses from the blood to the tissues, for they have a low partial pressure of oxygen in their vicinity. Thus in effect the oxygen moves from a region of high partial pressure (the blood) to a region of low partial pressure (the tissues) just as any gas goes from a high pressure region to a low pressure region.

A common example of the movement of a gas from a region of high pressure in a liquid to a region of lower pressure in a gas is seen when we open a bottle of a soft drink or beer. The carbon dioxide has a high partial pressure in the liquid, and as long as the bottle is capped, it has the same high pressure in the gas space above the liquid. But when we open the bottle, the gas pressure in the space above the liquid drops to atmospheric, and there is now a tendency of the dissolved gases to escape from the liquid. We see this as bubbles of gas. Somewhat the same thing occurs in the tissues, insofar as the movement of oxygen molecules from the blood to the cells are concerned, except of course that the movement takes place entirely in a liquid medium, and there are no bubbles. But the idea of the movement of the molecules of the gas under some sort of pressure difference is the same in both cases. The gas moves from a region of high pressure to a region of lower pressure, and the tissues are regions of low oxygen pressure because they are using up the oxygen molecules, and thus reducing their concentration, or pressure.

However the movement of oxygen in and out of the blood is not a simple process of solution and escape of a gas. The presence of a red pigment, hemoglobin, in the red cells of the blood radically alters the oxygen carrying properties of the watery solution that is blood plasma. These small round cells with a thinned out part in the centre — kind of like a doughnut without a hole — exist only to carry hemoglobin and not allow it to escape into the blood stream. Hemoglobin combines very avidly with oxygen and is absolutely necessary in order that all of the oxygen which we need can be carried in the blood. We may show the extent of this combination or binding by a curve in which the extent of binding is plotted against the partial pressure of oxygen to which the cell is exposed (see graph overleaf). Obviously, the higher the partial pressure of oxygen, the greater the binding. With zero partial pressure, or no oxygen, there is no binding. Notice though, that there is a saturation point. Above a partial pressure of 100 mm Hg of oxygen, there is little additional binding of oxygen — the hemoglobin is carrying just about all of the oxygen it can. As the partial pressure in the alveoli falls, the amount of oxygen which is carried by the hemoglobin also falls, but note that the reduction in carrying capacity is not proportional to the drop in oxygen partial pressure. At first, as the pressure is reduced, there is very little reduction in the carriage of oxygen, but then there is a rather abrupt drop. Translating this curve into terms which are of more immediate interest to us, we can say that at an altitude of about 10,000 feet, the hemoglobin is still about 95% saturated. Not too bad. At 20,000 feet it can still carry about 80% of its normal capacity, but the curve is now shifting rapidly, for at 23,000 feet the blood will only be carrying about two thirds of its capacity. At 28,000 the blood is only operating at about 50% of "full scale".



If we consider this binding curve only, it does seem as if we should be able to go to fairly high altitudes — eg. 20,000 feet, without too many problems, for there would appear to be enough oxygen reserve in the hemoglobin to allow for our needs. In fact this is not so, for the partial pressure of oxygen rapidly decreases with altitude, and this reduction means that normal metabolic reactions cannot occur. Other changes, especi-ally in the circulation, tend to increase the magnitude of the oxygen deficit. The brain is especially sensitive to these changes, and it is here that most of the trouble in hypoxia occurs. If we go to 10–15,000 feet, compensating changes occur in respiration and circulation, so in most individuals little effect is noted. However, in the range from 15–20,000 feet, compensatory reactions begin to be inadequate, and there is generally a degradation of mental processes and loss of critical judgement, muscular control and finally of consciousness.

Note again that deep breathing will not markedly alter the partial pressure of oxygen in the lungs, so it does little to alleviate the hypoxia at altitude. (I am disregarding some small compensatory changes which do take place.*) The only way to carry more oxygen is to inhale oxygen at a higher partial pressure — ie. from a suitable system. The main points I would like to make in this article are:

1 Oxygen is carried from the lungs to the body cells in combination with hemoglobin.
2 By virtue of the peculiar properties of this combination, we can carry sufficient oxygen to the tissues up to a certain altitude. After that, changes take place rapidly. Be warned!

To round out the story, it perhaps should be noted that the effect of carbon monoxide, found in cigarette smoke as well as in engine exhaust, is to reduce the oxygen carrying capacity of the hemoglobin. It is a very powerful poison in this respect. Further, though the

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** Breathing rate does increase naturally with reduced oxygen pressure which lowers the carbon dioxide in the blood. This makes the blood more acidic which allows the hemoglobin to become more saturated with oxygen.*

blood may carry adequate oxygen to the cells, there is no guarantee that the cells can use it. Some agents, notably cyanide, interfere with the ability of the tissues to use the oxygen transported to them, and hypoxia ensues just as certainly as if oxygen had been cut off.

The arithmetic of oxygen

Tony Burton

THE SEA LEVEL PRESSURE of the "Standard Atmosphere" is 760 mm (29.92 inches) of Hg, or 101.32 kilopascals (1013.2 mb). The composition of the atmosphere by volume is 78% nitrogen, 21% oxygen, and 1% other gases. Total air pressure reduces with altitude, and "standard" atmospheric pressure is:

1/2 of sea level at 17,970 feet,
1/4 of sea level at 33,780 feet, and
1/8 at 48,235 feet.

The body cannot store oxygen, and if it is withheld from the brain, unconsciousness will follow in about 20 seconds. A person can function with a reduced supply but at reduced efficiency. Above 10,000 feet one must breathe additional oxygen mixed with the air for normal needs. By 34,000 feet pure oxygen is required, and above that it must be delivered to the lungs under pressure. The ceiling for the unprotected body is about 48,000 feet as the high differential pressure of oxygen forced into the lungs will then expand them to the point where these overinflated "balloons" begin squeezing the heart. Above this altitude a pilot must wear a partial or full pressure suit to survive.

Let's do some arithmetic: at 34,000 feet, atmospheric pressure is 187.5 mm Hg, and gas pressure in the lungs from the air will be 100 mm Hg, which is the sea level value. This means that all the pressure in the mask must come from O_2 — you must breathe 100% O_2. At 39,000 feet, atmospheric pressure is 148 mm Hg and O_2 pressure is 63 mm Hg. This is the partial pressure of atmospheric O_2 near 10,000 feet, so above 39,000 feet we need oxygen delivered under positive pressure to maintain an adequate supply. Above 45,000 feet the oxygen pressure is less than the venous blood return O_2 pressure at those altitudes, so the transport of lung oxygen into the blood will cease. Only positive pressure in the mask will keep you alive.

Respiratory Gas Pressures (mm Hg)

	ambient		lung		
Altitude	P_{atmos}	O_2	O_2	CO_2	H_2O
0	759.97	159.21	103.0	40.0	47.0
5,000	632.46	132.50	81.0	37.4	47.0
10,000	522.73	109.51	61.2	35.0	47.0
15,000	429.01	89.88	45.0	32.0	47.0
20,000	349.50	73.22	34.3	29.4	47.0
25,000	282.45	59.17	30.4	27.0	47.0
pilot breathing 100% oxygen					
34,000	187.51	187.51	100	40	47.0
39,000	148.08	148.08	63	36	47.0
42,000	128.27	128.27	48	33	47.0
45,000	111.25	111.25	34	30	47.0

Table from p93, *Fundamentals of Aerospace Medicine* by Roy L DeHart

Other hazards of low pressure

Tony Burton

THERE ARE A LOT MORE SPACES within the body that contain air and other gases besides the lungs, so trapped gases have effects which can be severe. At 34,000 feet for example, with only a quarter the sea level pressure, the volume of any gas in the body will expand four times (if it can).

Air is contained in the ears and sinuses and normally will have free exit to the outside and will escape when it expands. On descent, no trouble will be experienced with the sinuses unless you are suffering from a bad cold or sinusitis. However the exit from the ear through the eustachian tube acts much like a one way valve. This tube can be opened by yawning, swallowing, or moving the jaw from side to side. This should be done routinely and often on descent since a large, rapid pressure change within the ear can cause vertigo. If these movements don't work, hold the nose and mouth closed and blow. This "valsalva" maneuver pressurizes the air tract and forces the eustachian tube open. This can be done with your mask on. If the ears remain blocked or are painful after landing, see a doctor. If you have been on oxygen for a considerable time, it may be necessary to clear the ears once or twice during the first hour after landing.

The pilot should *never* contemplate high altitude flight with any symptoms of a head cold. The resultant tissue inflammation may make it difficult or impossible to clear the ears on descent. This could result in a rupture of the eardrum, or, if equalization is forced with the valsalva maneuver, it could push infection into the ear from the eustachian tube.

A high altitude flight can trigger the unfortunate clue that you have an abscess in a tooth. The trapped gas pressing on the tooth nerve will cause severe pain which can only be stopped by descending again.

Accumulation of gas in the digestive tract is normal due to digestion and swallowed air. During ascent this gas will normally escape by passing flatus or belching. Problems can arise if pockets of gas in the gut remain trapped. This can cause cramping pains or even difficulty in breathing if the expanded gas presses on the diaphragm. These can be treated by holding altitude while loosening the seat belt, wriggling around, belching, etc. until gas is passed either direction. If this doesn't work — descend. If you are considering a high flight, don't eat gas producing foods such as pears, beans, cabbage or take aerated drinks before flight. Don't eat too fast as this will increase the amount of swallowed air, and don't eat too much.

By now you will appreciate that the human body is designed to work pretty well on the ground and is increasingly uncomfortable with the prospect of operating at high altitude.

Once above about 25,000 feet, you are putting yourself at rapidly increasing risk, so you must be fit, healthy, and sure of your cockpit survival gear. Above 28,000 feet at the top of the Livingstone Block, you are definitely in "crocodile country" and you should be there only because you have planned and are prepared for it, have a backup for an unserviceable oxygen system, and are going for a record or a trophy. You don't need to be this high for a Diamond and the view is just as great a mile lower down.