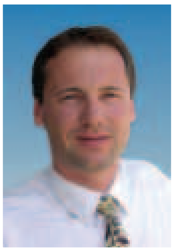
Hypoxia an Invisible Enemy

Cabin depressurization effects on human physiology



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When public air transportation first became commonly available, flights did not reach altitudes that represented a significant risk of reduced oxygen supply - called hypoxia - to either passengers or crew. However, in the late 1940s and 1950s aircraft were developed that allowed safe transport of the flying public at altitudes around 40,000ft, which have remained relatively constant since then.

DEFINITIONS OF HYPOXIA

Hypoxia is separated into four types:

- *Hypoxic hypoxia* is a condition caused by reduced barometric pressure, affecting the body's ability to transfer oxygen from the lungs to the bloodstream.
- *Histotoxic hypoxia* can be induced by the introduction of substances like alcohol or drugs into tissue, reducing its ability to accept oxygen from the bloodstream.
- *Hypaemic hypoxia* (or *anaemic hypoxia*) is a result of the blood being unable to carry oxygen, e.g. caused by exposure to carbon monoxide.
- *Stagnant hypoxia* results from the body's inability to carry oxygen to the brain, which can result from high gravity-forces causing blood to pool in the lower extremities of the body.

1 Introduction

Operating at high altitude without adequate understanding, training or equipment protection can be dangerous as shown by the following extracts from two accident reports:

'One of the first encounters with the dangers of high altitude flight was reported in 1862 when a balloon flight was made to study the effects of low ambient pressure. The balloon ascended to approximately 29,000ft and during the flight a series of "strange" symptoms, notably loss of visual and hearing capability, paralysis of arms and legs, and finally, unconsciousness occurred. The team could have been lost, but was saved by one member pulling the balloon valve rope with his teeth (his arms were already paralysed), to descend the balloon. The team recovered as the balloon descended, but this marked for the first time the risk of low ambient pressure.'

'In 1998 a decompression incident occurred on an aircraft at 35,000ft. Both the captain and the first officer had received altitude-chamber training during their previous military careers and knew about the effects of low cabin pressure. The first officer attempted to control the cabin rate of climb by switching to the standby pressurization system. When use of the standby system failed to improve

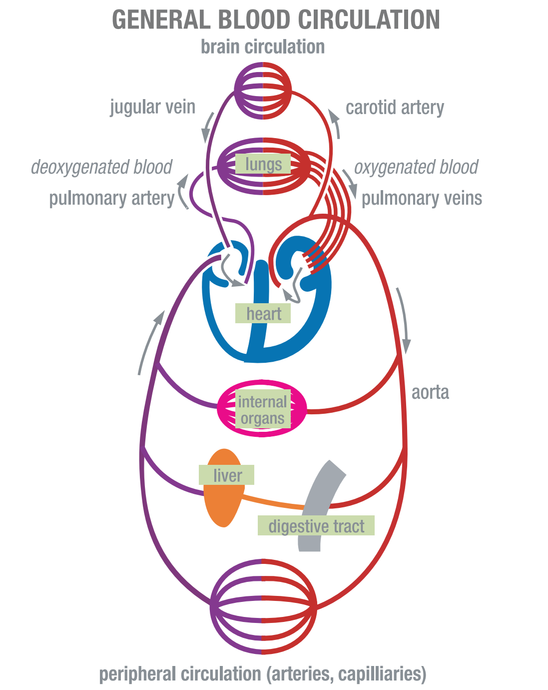
the situation, he donned his oxygen mask. The captain, who had been talking with a passenger who was visiting the flight deck, attempted to don his oxygen mask too, but in doing so he knocked his glasses to the floor. When trying to retrieve them he lost consciousness and slumped forward. The first officer attempted to help the captain but was unable to do this, so initiated a descent to 25,000ft. A short time later the first officer asked the senior flight attendant to assist the captain. To enter the flight deck the flight attendant had to remove her oxygen mask connected to the fixed cabin oxygen system. She decided not to use the portable oxygen equipment and went straight to the flight deck. Before being able to assist the captain she collapsed onto the floor. Once again, the first officer attempted to put on the oxygen mask for the captain, this time successfully. Soon afterward, the captain regained consciousness and was unaware he had been unconscious, which is a typical reaction from a victim of hypoxia.'

2 The hypoxia effects of a quick cabin depressurization

During a quick depressurization the partial pressure of oxygen in the lungs/alveolae reduces rapidly with the effect of reverse diffusion. This means that once the oxygen partial pressure in the alveolae has reached a level that is below the level in the blood, the blood oxygen moves out of the body back into the ambient air. This effect of reverse diffusion unfortunately further reduces the already very limited oxygen storing capability of blood and supports hypoxia effects. Holding of breath cannot stop the reverse flow since the pulmonary gas expansion would lead to serious lung injury.

Human physiology

Within the lungs the alveola provide the interface between air and blood. The blood which is returned from the body tissue into the alveolae has given away most of its oxygen so that the oxygen partial pressure in the lungs is higher than in the arriving blood. A process of diffusion then drives oxygen through the thin alveolar wall into the blood.

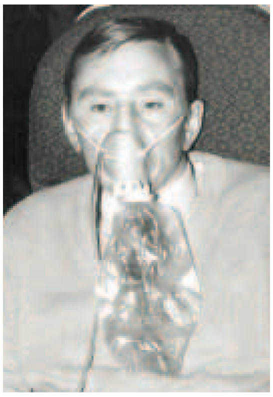


The most important parameters for the oxygen diffusion process are the oxygen percentage and barometric ambient pressure. Changing these parameters changes immediately the oxygen saturation level in blood and with it the oxygen supply to the body tissue. Unfortunately, there is no significant storage of oxygen in the human body, unlike many other chemical substances necessary to maintain life. The blood is the only storehouse for oxygen, and its capacity is very limited. Hence, the human body lives only a hand-to-mouth existence with its oxygen supply.

As the pressure of air in the atmosphere decreases with increasing altitude, the partial pressure of oxygen in the air reduces and with it the diffusion of oxygen into the body. Reduction of oxygen availability in the body results in loss of functions ranging from slight impairment up to death. It is the nervous system, in particular in the higher centres of the brain, and the eyes which have a high metabolism with no oxygen reserve. These are most sensitive to oxygen depletion and therefore are the first to be affected by a reduced oxygen supply.

For healthy persons altitude exposure up to 15,000ft is usually not hazardous since cardiovascular and respiratory compensatory mechanisms (faster breathing and increased pulse rate/blood circulation) act to maintain adequate oxygenation at the cellular level.

The effects of reduced oxygen supply to the body (hypoxia) vary between persons, depending on health, physical fitness, age, activity level and statistical scatter with the population. Pilots and flight attendants usually require more oxygen during an emergency than healthy, seated passengers and might therefore suffer earlier from hypoxia effects.



** Dalton's Law*
(1766 -1844)
In 1801, the English astronomer and chemist, John Dalton, discovered the pressure relationship among gases in a mixture. Dalton's Law states that the pressure exerted by a mixture of gases is equal to the sum of the pressures that each would exert if it alone occupied the space filled by the mixture.

Severe hypoxia caused by a significant reduction in cabin pressure is very dangerous for flight crew because:

- The victims of hypoxia rarely notice that they are about to pass out.
- Usually there is quickly a loss of critical judgment
- Most victims often experience a mildly euphoric state
- Thinking is slowed, muscular coordination is impaired

The only effective means of protection is the quick donning of oxygen masks as the first action - before troubleshooting!

Early type of shaped oxygen mask for passengers

3 Oxygen partial pressure

The concentration of oxygen in the atmosphere is constant at 20.95% at altitudes up to 100,000ft, which means that according to Dalton's Law* the oxygen partial pressure at sea level is 212mbar (20.95% of 1013mbar where 1013mbar is the standard atmospheric pressure at sea level).

As altitude increases above sea level the partial pressure of the component gases decreases consistent with the decrease in total atmospheric pressure. For example, the partial pressure of oxygen at 40,000ft is reduced to 39mbar only, which is far too inadequate to support human metabolism.

One means to increase oxygen partial pressure is to increase the oxygen concentration in breathing air. At 40,000ft cabin altitude an oxygen partial pressure of maximum 188mbar can be achieved by breathing pure oxygen (100% oxygen concentration without overpressure).

Another additional means for hypoxia protection is positive pressure breathing, which is usually found in modern crew oxygen masks and means the delivery of pure oxygen under pressure into the respiratory tract. For civil applications positive

Current oxygen mask for passengers

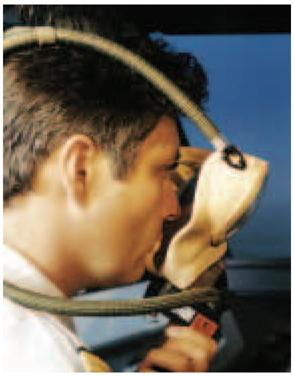
pressure breathing is able to increase additionally the oxygen partial pressure by around 20 to 30mbar provided that the overpressure condition is limited to some minutes only. This means that at 40,000ft it requires 100% oxygen concentration of the breathing gas combined with positive pressure breathing to achieve sea level equivalent conditions. Positive pressure breathing requires some training and is tiring and inconvenient, which is the rationale for having so far provided this protection feature to flight crew only (for short time use only).

*Flight crew oxygen mask **

4 Time of Useful Consciousness

In the 'World of Hypoxia' the Time of Useful Consciousness (TUC) is a very important parameter. For low ambient pressure conditions it indicates the time available to perform purposeful activities, such as oxygen mask donning or aircraft control. Beyond this time frame mental and physical capabilities are dangerously impaired and finally result in unconsciousness and potentially death.

As shown in the table on the right, TUC is negatively correlated with altitude. It is important to note that even if activities are performed within the TUC time frame there is a significant deterioration of work rate and mental capability, which is correlated with the time spent at low pressure conditions (at the end of the TUC time frame, performance is much lower than at the beginning).
The TUC is the 'Window of Opportunity' for donning an oxygen mask and can be very limited so must take overriding precedence over any other activities.



Mask straps inflated

Mask in place

5 Time of Safe Unconsciousness

Some experts believe that for passengers - in contradiction to the flight crew - a short period of unconsciousness during cabin depressurization can be tolerated since they are not performing an operational task. Unconsciousness is a clear sign of insufficient oxygen supply to the brain and it is obvious that this time can only be very short before permanent brain damage occurs. So far, it has not been possible to associate a specific time frame for the safe time of unconsciousness.

The uncertainties in extrapolation of animal data and the wide variability in individual tolerances have so far prevented determination of a commonly agreed value for Time of Safe Unconsciousness (TSU) among human physiology experts. It is believed that a safe time of unconsciousness is somewhere between 90 seconds and 4 minutes.

TIME OF USEFUL CONSCIOUSNESS

20,000ft	All unacclimatized persons lose useful consciousness within 10 minutes
25,000ft	Useful consciousness is lost after 2.5 minutes or less
30,000ft	TUC: approx. 30 seconds
37,000ft	TUC: approx. 18 seconds
45,000ft	TUC: approx.15 seconds

These data on TUC are averaged values based on tests with healthy individuals when breathing ambient air (no supplemental oxygen provided).
A large individual variation in the effects of hypoxia has been found. There is evidence that TUC is shorter for people exposed to stress conditions.

* Manufacturer EROS

6 Oxygen equipment on civil aircraft

On modern aircraft oxygen equipment is installed to provide adequate protection against the damaging effects of hypoxia in case of cabin depressurization:

For flight crew there are usually quick donning oxygen masks installed, which can be donned with one hand in less than 5 seconds. The mask straps are combined with elastic tubes that inflate and stiffen when the mask is taken from its stowage, allowing the mask to be easily put over the head with one hand. Once the grip on the mask is released, the tubes deflate and their elastic characteristics ensure a perfect fit. The required oxygen concentration of the breathing air is automatically adapted to the cabin pressure.

For the passenger oxygen supply the continuous flow concept is used on all Airbus aircraft. Oxygen is delivered continuously to an expandable oxygen bag where it is conserved during exhalation, so it is available during the next inhalation to supplement the steady oxygen flow.

It was decided at an early stage in passenger oxygen mask development that the untrained civilian population should not be expected to recognize the correct orientation for a shaped mask, and it was required that a mask should be operable in any position in which it might be donned by the user.
A second basic requirement was a universal size, which finally defined the well-known cylindrical mask body.

Effect on human physiology of moderate cabin altitude

Very large numbers of aircrew and passengers have been exposed to breathing air at cabin altitudes up
to 8,000ft over the last 60 years without significant deleterious effects. Although exposure to this altitude reduces the oxygen partial pressure in the pulmonary tract the tissues of the body are maintained well above the required level.

Some airlines still allow smoking in the aircraft cabin, which results in carbon monoxide inhalation with the smoke. Carbon monoxide has a 240-times greater tendency than oxygen to attach to red blood haemoglobin, thus inactivating a large amount of haemoglobin as an oxygen carrier. It has been found that the hypoxia effects from carbon monoxide and altitude are additive; hence chronic smokers are at a higher equivalent altitude than non-smokers in terms of blood oxygen supply.

Also, alcohol poisons body tissues in such a manner that they cannot use oxygen properly. Usually, it is noticed by passengers that the physiological effect of alcohol consumed during flight is more intense than at sea level, which is due to the additive hypoxia effects of alcohol and altitude.

Extract of the prime requirements

GENERAL
- CS/FAR 25.841 (a): Maximum cabin pressure altitude under normal operation: 8,000ft
- CS/FAR 25.841 (a): Maximum cabin pressure altitude after any probable failure condition in the pressurization system: 15,000ft
- FAR 25.841 (a) (2) (i): Maximum exposure time to cabin pressure altitude exceeding 25,000ft: 2 minutes
- FAR 25.841 (a) (2) (ii): Exposure to cabin pressure altitude that exceeds 40,000ft: Not allowed

CABIN OCCUPANTS
- CS/FAR 25.1443 (c): Provides oxygen system performance data on oxygen flow and required partial pressure of oxygen
- CS/FAR 25.1447 (c) (1): The total number of masks in the cabin must exceed the number of seats by at least 10%
- CS/FAR 25.1443 (d): Defines oxygen flow for first-aid oxygen equipment (for cabin depressurization treatment)
- JAR OPS 1.760/FAR 121.333 (e) (3): Requires first-aid oxygen for at least 2% of passengers
- JAR OPS 1.770 (b) (2) (i)/FAR 121.329 (c): Defines the percentage of passengers that need to be provided with supplemental oxygen (cabin pressure altitude dependent)

FLIGHT CREW
- CS/FAR 25.1443 (a) & (b): Provides oxygen system performance data on oxygen flow and required partial pressure of oxygen
- CS/FAR 25.1447 (c) (2) (i): For aircraft operating above 25,000ft quick donning oxygen masks are required for the flight crew which can be donned with one hand within 5 seconds
- FAR 121.333 (c) (2) (i) (A): One flight crew member needs to wear permanently his oxygen mask when the aircraft is operated above FL410
- FAR 121.333 (c) (3): In case one flight crew member leaves the controls the remaining pilot needs to use his oxygen mask when the aircraft is operated above 25,000ft

7 Airworthiness requirements

The Airworthiness authorities have identified the risk of hypoxia and have created requirements (see table on the left).
Also, after an accident in the USA the FAA initiated a Special Certification Review (SCR) on pressurization systems. The SCR recommends that the aircraft flight manual (for aircraft certified for flights above 25,000ft) require in the emergency procedures the donning of oxygen masks as the first crew action after a cabin altitude warning.

This highlights again the importance of immediate donning of oxygen masks when cabin depressurization occurs.

8 Conclusion

The first step for any flight crew member faced with cabin depressurization should be the immediate donning of an oxygen mask. Any delay in donning a mask will significantly increase the risk of losing consciousness before cabin pressure is regained. Severe hypoxia leads usually to the loss of critical judgement combined with a mildly euphoric state, which makes hypoxia very dangerous for flight crew. This is highlighted also in the FAA Special Certification Review that was issued some years ago on the effects of cabin depressurization.

Moreover, in case of rapid cabin depressurization a quickly accomplished emergency descent is often the only means of fast re-oxygenation of passengers that were unable to protect themselves against hypoxia by using the passenger oxygen masks provided. Severe hypoxia is very dangerous for unprotected passengers and requires a quick return to an adequate cabin pressure or where not possible (above high terrain), it requires a check by the flight attendants that the passenger oxygen masks are correctly used.

For a long time transport aircraft have been equipped with oxygen systems for flight crew and passengers that provide an adequate protection against hypoxia. As long as these oxygen systems are used according to their simple procedures the invisible enemy hypoxia poses little danger to flight crews and passengers.

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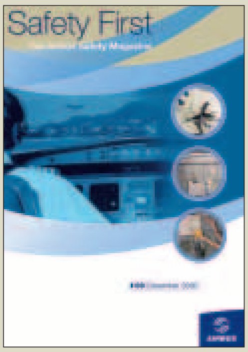

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