Chapter 3

Atmosphere and Gas Laws

Much of what will be covered in this course is based on the air medical escort having an understanding of the changes he or she, the patient, and medical equipment undergo as a result of exposure to increased altitude. A thorough understanding of Earth's atmosphere and the natural laws that effect gasses will allow the air medical escort to more successfully carry out his or her duties during air medical transport.

Learning Objectives

Upon completion of this chapter, the participant should be able to:

- State the three major characteristics/functions of the atmosphere.
- List the two primary gases in the atmosphere.
- List the five divisions of the atmosphere and the corresponding altitudes.
- State the relevance of Boyle's Law in the air medical environment.
- State the relevance of Dalton's Law in the air medical environment.
- State the relevance of Henry's Law in the air medical environment.
- State the relevant differences between a rapid and a slow decompression of an aircraft cabin.
- Describe the effects of decompression on the cabin of an aircraft.
- Describe the effects of decompression on patients and crew.
- Describe the effects of decompression on medical equipment and devices.

The Atmosphere

The atmosphere is a gaseous envelope surrounding the earth. It provides life support (oxygen), protection from ultraviolet radiation, and acts as a layer of insulation to keep in heat.

Composition of the Atmosphere

It is made up of a combination of water vapor and gases. The two primary gases are nitrogen (78%) and oxygen (21%). The remaining one percent is carbon dioxide (0.03%) and other rare gases.

Physical Divisions of the Atmosphere

The atmosphere has five major divisions.

1. Troposphere—from Sea Level to about 35,000 feet.
   - This is the division where weather occurs.
   - Temperature decreases 2ºC or 3.6ºF for each 1,000 feet of ascent.
   - Most flight operations occur in the troposphere.
2. Tropopause—the isothermal layer forming a barrier between the troposphere and stratosphere.
3. Stratosphere—from about 35,000 feet to about 50 miles above the ground, it contains the ozone layer and "Jet Stream."
4. Ionosphere—from about 50 miles to about 600 miles above the ground.
5. Exosphere—from about 600 miles to 1,200 miles above the ground.

Air Pressure

The weight of the atmosphere pushes down upon the earth's surface. One can imagine one-inch square blocks of air stacked one on top of another all the way up to the outer reaches of the atmosphere. The pressure exerted by the column of air (the blocks) is known as the atmospheric pressure.

- This pressure is commonly measured in terms of pounds per square inch (psi) or millimeters/inches of mercury (mmHg/inHg).
- At sea level the atmospheric pressure is 14.7 psi, or 760 mm/Hg.

Zones Within the Atmosphere

There are three physiologic subdivisions or "zones" within the physical divisions of the atmosphere. These physiologic zones are most closely linked to concerns about patient care.

1. The Physiological Zone is between sea level and 10,000 feet above sea level.

    - Oxygen levels are sufficient to keep a normal, healthy person fit without the aid of special protective equipment, despite the fact that barometric pressure drops by about a third (760 mm/Hg to 523 mm/Hg) at 10,000 feet.

    - Changes in pressure encountered during ascents or descents in this zone may produce middle ear or sinus problems.

    - Exertion, lack of time to adapt and many acute medical problems may cause additional difficulty at the upper portions of this zone. At the upper region of this zone, respiration and heart rate increase and vessels dilate in the attempt to adapt to the decreased atmospheric pressure and concentration of oxygen.

2. The Physiologically Deficient Zone is found between 10,000 and 50,000 feet above sea level.

    - Atmospheric pressure decreases to 10% of sea level (at 50,000 feet pressure equals 87 mm/Hg).

    - The partial pressure of oxygen is also decreased (see Dalton's Law). This results in noticeable physical (e.g. trapped bowel gas) and physiological (e.g. hypoxic) problems.

    - Supplemental oxygen may be indicated at the lower levels of this zone, and is definitely indicated as the altitude increases.

3. The Space Equivalent Zone lies between 50,000 feet and the limits of the atmosphere.

    - This zone is hostile to human life. Exposure at these altitudes rapidly leads to death in the absence of an artificial environment.

- At 63,000 feet (Armstrong's Line), pressure decreases to 5% of that at sea level and the boiling point of body fluids drops to 98.6º F. Above this altitude blood will "boil" as the gases in it come out of solution. (See Henry's Law).

Physiological Divisions of the Atmosphere

Altitude	mm/Hg	Zone
50,000	97 or less	Space Equivalent Zone
10,000	523	Physiologically Deficient Zone
Sea Level	760	Physiological Zone

Source: Aeromedical Training for Flight Personnel (FM 1-301) March 1983 (ATFP)

The Gas Laws

Several gas laws are important for air medical escorts to understand. These laws describe how changes in altitude affect air medical crews, patients, equipment and the environment within aircraft.

Boyle's Law

Boyle's Law states that *at constant temperature the volume of gas is inversely proportional to the pressure on it.*

$$\frac{V_1}{V_2} = \frac{P_2}{P_1} \quad \text{or} \quad P_1V_1 = P_2V_2$$

V_1 = the initial volume
V_2= the final volume
P_1= the initial pressure
P_2= the final pressure

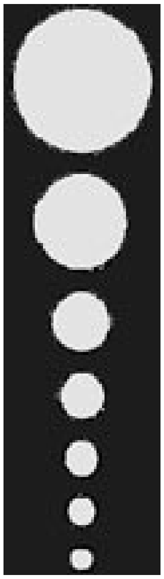
Relevance

Boyle's Law means that gas:

- Expands as altitude increases, because there is less pressure on it from the surrounding atmosphere.

- Contracts when altitude decreases or if taken to a deeper depth underwater.

This is illustrated in the figure below.



43,000 feet = 6 times larger

34,000 feet = 4 times larger

25,000 feet = 2.5 times larger

18,000 feet = 2 times larger

10,000 feet = 1.5 times larger
5,000 feet = 1.25 times larger
Sea Level

Moisture Content

The moisture content of a gas affects the degree of expansion.

- Body water saturates gases within the body.
- Wet gas occupies a greater volume than dry gas.
- Boyle's Law affects the wet gases within the body even more than it does dry atmospheric gases.

After hypoxia, changes in gas volume is the most important physiological consequence of flight. Examples of things affected by this change in air volume include: air in IV lines, pressure infuser bags, air splints, vacuum splints, vacuum mattresses, pneumatic anti-shock garments (PASG), the stomach, sinuses, ears, a pneumothorax, and an ET tube cuff. The air in any of these will expand as altitude increases.

Dalton's Law of Partial Pressures

Dalton's Law of Partial Pressures states that *the total pressure of a gas mixture is equal to the sum of all the gases in the mixture.*

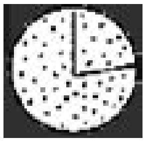
$P_t = P_1 + P_2 + P_3 \ldots P_n$

P_t = Total pressure of the gas mixture
P_1= the partial pressure of gas 1
P_2= the partial pressure of gas 2
. . .
P_n= the partial pressure of gas n

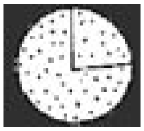
Relevance

Dalton's Law of Partial Pressures means:

- Oxygen makes up 21% of the atmosphere and accounts for 21% of the total atmospheric pressure.
- The fractional pressure of each gas is its "partial pressure." At sea level, the partial pressure of oxygen is 160 mm/Hg, which is 21% of the total atmospheric pressure of 760 mm/Hg. As the atmospheric pressure decreases with an increase in altitude, the partial pressure of oxygen will also decrease, even though it will still remain 21%. The pictures below illustrate this.



Sea level 21% = 160 mm/Hg
Partial pressure of oxygen **Total Pressure = 760 mm/Hg**



10,000 feet 21% = 110 mm/Hg
partial pressure of oxygen **Total Pressure = 522.6 mm/Hg**

Another way to understand Dalton's Law is to understand how it affects a person.

- The transfer of oxygen molecules from the lungs to the bloodstream is dependent on a pressure gradient. Pressure helps the oxygen molecules go across the alveolar membrane. The higher the pressure gradient, the easier the oxygen molecule moves.
- As the atmospheric pressure decreases with increasing altitude, the partial pressure of oxygen also decreases. The decreased partial pressure makes it harder for the oxygen molecules to cross the alveolar membrane and get into the bloodstream. The percentage of molecules of oxygen in the air does not change

with altitude, but the molecules are more spread out, so fewer are inhaled with each breath. This is compounded by the effect of Boyle's Law.

Atmospheric pressure is the sum of all the partial pressures of the constituent gases. So, an increase in altitude results in reduction of both the total atmospheric pressure and the partial pressure of oxygen, nitrogen, or any other gases. The chart below illustrates the changes in partial pressure.

Altitude	Total Pressure	O_2 mm/Hg	N_2 mm/Hg	Other mm/Hg
Sea Level	760	160	593	7
10,000	523	110	408	5
18,000	379	80	296	3
25,000	282	59	221	2
34,000	190	40	148	2
48,000	95	20	74	1
63,000	47	10	37	<1

Numbers are rounded for simplicity.

The threat of hypoxia increases as altitude increases. The loss of available oxygen may not be initially noticed at low altitudes, but the effects are measurable at levels as low as 4,000 feet. Chapter 4 discusses hypoxia and its effects in greater detail.

Charles's Law

Charles's Law states that *the volume of a gas will vary directly with the absolute temperature, given that the mass and pressure remain constant.* This law is important for air medical escorts to understand because it affects the volume in air filled devices.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

V_1 = the initial volume
V_2 = the final volume
T_1 = the initial temperature
T_2 = the final temerpature

Relevance

An inflated balloon will shrink in cold temperatures and will re-expand when it is placed back in a warm temperature.

Likewise, air filled devices like air splints and PASGs, which are not rigid, will expand or contract as the temperature increases or decreases.

Henry's Law

Henry's Law states that *the amount of gas dissolved in solution varies directly with the partial pressure of that gas over the solution.* Stated another way, the higher the pressure exerted on the solution, the more gas the solution will hold.

Henry's Law is well demonstrated by the example of the gases held under pressure in carbonated soda. Removing the cap exposes the liquid inside to a pressure less than what is required to hold the gas (carbon dioxide) in solution; the gas immediately begins to escape in the form of bubbles.

Henry's Law is important for air medical escorts to understand when they are transporting patients who have been diving (e.g. scuba diving, or in a hyperbaric chamber, etc.). Divers have more gas (N_2) dissolved in their blood due to the increased pressure from the water on their bodies during a dive (which can last for up to 24 hours after diving). Taking people who have been diving recently to a higher altitude releases that gas quickly, causing problems like acute decompression sickness (e.g. the "Bends").

Law of Gaseous Diffusion

The Law of Gaseous Diffusion states that a *gas will diffuse across a semi permeable membrane from an area of a higher concentration (pressure) to an area of lower concentration (pressure).*[1] What this means is that oxygen will move across the thin walls that separate areas in the body based on oxygen levels. There is more oxygen in the lungs so it moves from the alveoli across membranes into blood cells and from blood cells into tissues. Carbon dioxide levels are higher in cells, so it moves into the blood stream then into the lungs and is exhaled from the body.

Pressure Gradient at Altitude	
Sea Level	10,000 Feet
Alveol pO_2 = 100 mm	Alveolar pO_2 = 60 mm
Arterial pO_2 = 40 mm	Arterial pO_2 = 34 mm
Difference = 60 mm	Difference = 26 mm
Arterial Sat. = 98%	Arterial Sat. = 87%

The chart at left shows that when there is a larger pressure gradient (difference) between the lungs and in the blood, more oxygen moves into the lungs and the arterial saturation is higher.

This fact is important for air medical escorts to know because, above 33,700 feet, even 100% oxygen by non-rebreather won't keep a human

[1] *United States Air Force Flight Surgeons Guide* (via Internet) wwwsam.brooks.af.mil/af/files/fsguide/HTML/00_Index.html (sic).

saturated. In addition, patients are rarely in ideal physical condition. They often have other factors that confound attempts to oxygenate them. There may come a point (altitude) at which medical providers can't provide enough oxygen to the patient to maintain adequate oxygenation.

Other Gas Laws of Note

Graham's Law

Graham's Law states that *the rate of diffusion of a gas through a liquid medium is directly related to the solubility of the gas and is inversely proportional to the square root of its density or gram molecular weight.* This means that the better a gas dissolves, the better it diffuses.

For example, carbon dioxide is more soluble than oxygen. It is approximately 19 times more diffusible than oxygen.

Gay Lussac's Law

Gay Lussac's Law states that *if the volume and the mass remain constant, the pressure exerted by a gas varies directly with the absolute temperature of that gas.* This means that the hotter the gas the higher the pressure; the cooler the gas the lower the pressure.

- Oxygen bottles will show an increase in indicated pressure as they warm.
- Oxygen bottles will show a decrease in indicated pressure as they cool.

Poiseulle's Law

Poiseulle's Law states that the volume of air inspired is directly related to the gas pressure gradient between the atmosphere and the lung alveoli and is inversely related to the resistance of opposing airflow. This means that the less pressure there is outside the body, the less air goes inside the body.

Decompression

General

Many aircraft cabins are pressurized to allow occupants to remain in a normal physiologic state, without having to breathe supplemental oxygen, during the flight.

A loss of cabin pressurization is referred to as decompression. Decompressions may be rapid or slow. Either situation poses a serious risk to medevac patients and crew due to the decreased levels of oxygen in the cabin.

Pressurized planes usually fly at altitudes above those a person can tolerate without supplemental oxygen. Some are equipped with oxygen masks that will pop down when the plane depressurizes and others require manual deployment of the masks. In either event, the air medical escort should **place his/her own mask on first**, then assist the pilot with his/her oxygen mask if not already on, and then assist others on-board. Air medical escorts cannot help anyone if *they* are not conscious!

Once depressurization has occurred, the pilot of the aircraft will want to get the plane to a lower altitude where all personnel can breathe in the non-pressurized environment. This may be one of the most frightening aspects of rapid decompression, as the pilot will perform a rapid descent to an altitude around 10,000 feet. Although in a steep descent, the plane usually is not in danger of crashing.

It is important that air medical escorts understand the effects of decompression on the cabin, crew, patient and equipment as well as knowing what to do should it occur. The most immediate effects of cabin decompression relate to the natural flow of gases from high to low pressure areas in an attempt at equalization. (Decompression itself is no more than the rush of air out of the relatively high-pressure cabin environment.)

Effects on People

Symptoms which may be felt by occupants of the aircraft include:

- Dyspnea.

- Decreased color perception/blurred vision/tunnel vision.
- Headache.
- Apprehension.
- Euphoria.
- Fatigue.
- Numbness/tingling/cold or hot flashes.
- Clumsiness/giddiness.

Signs exhibited by crew:	Signs exhibited by patients:
Increased pulse/respirations.	Increased pulse/respirations.
Euphoria.	Euphoria.
Loss of coordination.	Loss of coordination.
Confusion.	Confusion.
Belligerence.	Belligerence.
Decreased ability to make good judgments.	Worsening of pre-existing hypoxia.
	Expansion of trapped gas inside hollow organs affecting Pneumothorax Skull/facial fractures Bowel obstruction
Cyanosis.	Cyanosis.
Unconsciousness.	Unconsciousness.

The effects of cabin decompression include euphoria, confusion, decreased ability to make good judgments, and a lack of coordination. The onset of these symptoms may render occupants incapable of taking the necessary steps to correct the hypoxia associated with decompression. While they may be awake, they simply cannot do what is necessary.

The amount of time a person has before they are no longer able to act effectively is shown in the Time of Useful Consciousness Table. These figures are averages and may be influenced by individual tolerances. Note that individuals generally have half as much time-of-useful-consciousness in a rapid decompression as they do in a slow decompression.

Time of Useful Consciousness

Altitude (feet)	Slow	Rapid
43,000	9–12 seconds	4.5–6 seconds
40,000	15–20 seconds	7.5–10 seconds
35,000	30–60 seconds	15–30 seconds
30,000	1–2 minutes	30–60 seconds
28,000	2.5–3 minutes	1–1.5 minutes
25,000	3–5 minutes	1.5–2.5 minutes
22,000	8–10 minutes	4–5 minutes
18,000	20–30 minutes	10–15 minutes

Effects on the Cabin

The effects of decompression on the cabin include:

- Cold. Temperature decreases 2º C or 3.6º F for each 1,000 feet of ascent.
- Fog. Cold air doesn't support as much moisture so fog forms. (The dew point is the temperature at which dew forms).
- Noise. In a rapid decompression the air rushing out of the cabin creates a lot of noise. The engine and the wind sounds louder because of the breach in cabin integrity.
- Debris and equipment flies around the cabin. This may be due to:
    - The movement of air from the pressurized cabin to the outside.
    - The wind caused by traveling at high speeds.
    - The flight crew attempting to descend rapidly to around 10,000 feet.

Effects on Equipment

If the aircraft decompresses, there will be an immediate increase in air volume (Boyle's Law). The results can include:

- Gas-filled devices will rapidly expand and cause increased pressure on the patient, including:
    - Air splints.
    - PASG.
    - ET tube cuff.
    - Expansion of air remaining in IV bags or bottles, which could cause a potential air bolus into the patient or dislodge the IV tubing from the bag or bottle.
    - Loss of medications from pre-filled items like Bristojets, tubex syringes, etc.

Causes

Although uncommon, there are many things that can cause a loss of pressurization. Examples include:

- Mechanical failure of the compressor system.
- Loss of engine power.
- Loss of the airtight seal between the cabin and the external environment.

What to Do

- Plan ahead. Know what to do if and when decompression occurs.
- Secure equipment on each and every flight.
- Get rid of air in IV bags.

- Know how to put on aircraft oxygen masks.
- Discuss what to do and what could happen with the patient and non-medical escorts during the preflight briefing.
- Know the signs and symptoms of hypoxia.
- **Remember to place one's own mask first!**

Summary

Healthy humans are adapted for life within the Physiological Zone, which extends upwards to 10,000 feet above sea level. Most of our patients are not healthy; they have a disease process or injury that inhibits their ability to adapt to changes in altitude. Often they require assistance, in the form of supplemental oxygen, even at modest increases in altitude, due to decreased partial pressures of oxygen (Dalton's Law).

Since gas expands as altitude increases (Boyle's Law), the air medical escort needs to be mindful of things (persons or equipment) that contain gas and consider the implications of the expansion of that gas.

Alaska and the airborne environment both offer a wide diversity in temperatures. Increases in temperature tend to expand non-rigid, gas-filled devices, possibly leading to increased pressure on the patient, and temperature decreases causes them to contract. In rigid devices or where there is no room for expansion, the pressure exerted on the walls of these devices will increase with increases in temperature and decrease with decreases in temperature (Charles's Law).

The death of golfer Payne Stewart, whose Learjet crashed in South Dakota, illustrates the deadly effects of cabin decompression. A slow decompression may be insidious; occupants may not recognize that they are in trouble before they have exceeded the time of useful consciousness. While just as deadly, a rapid decompression is hard to miss. Since occupants only have half as much time of useful consciousness, in a rapid decompression, it is imperative that air medical escorts prepare themselves, their patients and others accompanying them for the possibility of a rapid decompression. Remember, the escort can only help others if they themselves remain conscious—they must use their own masks first!