EMS Subspecialty Certification Review Course

1.4.4 Flight Physiology
   1.4.4.1 Effects of altitude on patient management
   1.4.4.2 Effects of altitude on healthcare providers

Question

A recent post op (<24 hours) patient with a multiple enterotomies requires aeromedical evacuation. A functioning nasogastric tube should be in place due to the physiologic effects of

A. Boyle’s Law  
B. Dalton’s Law  
C. Henry’s Law  
D. Levy’s Law

Learning Objectives

Upon the completion of this section participants will:

- Understand basic principles of physiologic effects of atmospheric pressure
- Understand risks to patients and caregivers due to altitude
- Understand and describe applicable physical laws of gases which may negatively effect physiology
- Understand and describe physiologic stressors of flight
1. Altitude changes, even if modest, can present challenges to patient stability as well as caregiver performance. A quick example, is world class athletes who live at sea level suddenly competing at altitude. Generally, they will need some period of physiologic adjustment to perform at same competition level. Conversely, many athletes train at altitude prior to competing at sea level to enhance physiologic performance.

2. As gas molecules possess molecular weight, atmospheric pressure is tied to gravity and measured in Pounds per square inch-PSI (14.7), inches (29.92), or millimeters of mercury (760). Said in another way the more gases over the top of you, the greater the pressure and inversely, increasing altitude leads to lower pressures and availability of oxygen. Generally between sea level and 5,000 ft. the average person does not perceive pressure changes but critically ill patients may be at risk of de-compensation at even modest increase of altitude.

3. While physiologic function is generally normal to 12,000’ altitude (troposphere) even healthy people begin to feel the affects of altitude on oxygenation at around 7000’ which is the pressurization level of aircraft. Altitude above 17-18,000’ feet becomes more precarious and mountain climbers call altitudes above 20’-22,000 ft. the “death zone.”

4. Risks to patients from altitude include hypoxia, gas expansion and contraction during ascent and descent, effects of low humidity, temperature, and barotrauma.

Atmospheric Considerations

- Composition
  - 78% nitrogen, 21% oxygen at all altitudes
- Pressure is due to the weight of the gases
  - Decreases with altitude, predictably
- Gases are subject to physical laws
  - Gases in our bodies will change with the environment

Flight Physiology

There are 5 basic laws of gases which affect physiology

- Boyle: The effect of altitude on gas volume
- Dalton: The effect of altitude on oxygen availability
- Henry: Gas equalization due to pressure changes
- Charles: The effect of temperature on gas volume
- Graham: Diffusion of gases from higher to lower concentrations
There are five basic laws of affecting gases and physiology:

• **Boyle’s:** At constant temperature, the volume of gas is inversely proportional to the pressure – gas expands at altitude. E.g., expansion of a pneumothorax (need to monitor and prospectively consider placement of a chest tube), air in the GI tract (need NG especially if ventilated), ET cuffs and air splints expand and can cause localized barotrauma.

• **Dalton’s:** Total pressure of a mixture of gases is equal to the sum of the partial pressures of the gases — as altitude increases, pressures decrease and while concentration is still the same there are less molecules in any given space, hence less molecules of oxygen which can lead to hypoxia. A relatively stable patient at sea level may decompensate without added FiO2 at altitude. Pilots and medical crew in unpressurized aircraft may need supplemental oxygen. The effect of Dalton’s law is seen in compromised night vision, eye injuries, need for higher FiO2, potency of some medications (particularly beta blockers), and patients with anemia <7 Hgb or <25 Hct may decompensate.

• **Henry’s:** The quantity of gas dissolved in a liquid is proportional to the partial pressure of gas in contact with the liquid – gas wants to equalize into surrounding (e.g. soda pop going flat when exposed to ambient pressure). Patient issues resulting from Henry’s law relate to decompression sickness (i.e. “the bends”) caused by rapid ascent in which nitrogen bubbles out of blood. Divers are at risk for decompression syndrome for up to 24 hours after dive.

• **Charles’s:** If pressure is constant the volume of a gas is proportional to its temperature. Gas expands when heated (think explosions of un-vented gas tank) and contracts when cooled. Increase in altitude decreases pressure and consequently temperature. This can improve aircraft performance but thermally challenge a patient. Changes in temperature increase metabolic rate, heart rate, and oxygen demand with potential decompensation in compromised patient.

• **Graham’s law:** Gas will diffuse from higher to lower concentration (i.e. normal cellular respiration). Effect on critically ill patient is lower concentration / availability at altitude may require ventilation in addition to increased FiO2.

### Boyle’s Law

- **Volume is inversely proportional to pressure**
  - Gases expand when pressure is decreased
  - Ascending in a pool, bubbles get bigger
  - Gas expansion and contraction problems
    - Pneumothorax
    - Middle ear & sinuses
    - Dental procedures
    - Stomach & intestines

### Dalton’s Law

- **Total barometric pressure = sum of partial pressures**
  - (pressure of each gas present)
  - Partial pressure = (Total pressure)(% of gas)
  - Without adequate partial pressure of oxygen, you cannot absorb oxygen in your lungs
  - Remember: As you ascend, the percentage of oxygen remains constant, but partial pressures decreases
Henry’s Law

- The amount of dissolved gas in a liquid will decrease if the pressure around the liquid decreases
- When pressure is released, gas comes out of solution in the form of bubbles
- These bubbles in the body cause evolved gas problems (decompression sickness)
- Divers should wait to fly until 12-24 hours after diving

Graham’s Law

- Gases diffuse from higher to lower concentrations
  - Impacts normal gas exchange and cellular respiration
- Rate of diffusion of a gas through a medium is:
  - Directly related to the solubility of the gas
  - Inversely proportional to the square root of its density
  - E.g. improved diffusion of oxygen with heliox versus air

Charles’s Law

- If pressure is constant the volume of a gas is proportional to its temperature
  - Gas expands when heated (think explosions of un-vented gas tank) and contracts when cooled
  - Increase in altitude decreases pressure and consequently temperature
  - Changes in temperature increase metabolic rate, heart rate, and oxygen demand with potential decompression in compromised patient.
Bonus: Gay-Lussac’s Law

• Pressure and temperature are directly related when volume is constant

• E.g. Pressure in an oxygen tank decreases as the temperature decreases

Physiological Zones

• Physiological Zone – sea level to 10,000’
  – We can adapt in this zone

• Physiological Deficient Zone – 10,000’ to 50,000’
  – Majority of commercial flying
  – Hypoxia due to altitude
  – Trapped gas problems

And a final law... Murphy’s Law

“Whatever can go wrong will go wrong,
and at the worst possible time”

• If you ignore the previous gas laws, Murphy’s Law applies
Aeronautical Considerations

- Different types of aircraft require different strategies to manage patients as well as crew protective strategies.
- Altitude is described in relation to sea level (MSL) or ground level (AGL).
- **Helicopters**: Limited range (<150 mi);
  - Altitude: MSL to 15,000 feet (usually 1,000 to 5,000 feet AGL).
- **Fixed wing turboprops**: Mid range (150 – 1,000 mi);
  - Altitude: 6,000 to 18,000 feet (may require pressurization).
- **Jets**: Long range (>500 mi);
  - Altitude: ~ up to 40,000 feet (require pressurization).

+ In general, useful range of a helicopter is 150 nautical miles and operations are conducted 1,000-5,000’ above ground and tied to operating environment.
+ As altitude increases, the helicopter’s rotors or “wings” lose efficiency in both lift and forward motion. A helicopter’s main rotors are both its wings, lift and propulsion.
+ Helicopter operations above 10-12,000’ MSL want to have strategy for supplemental oxygen for pilot and crew due to potential degradation of physiologic performance.
+ Fixed wing turboprops are generally in the 150-1000 mile range losing efficiency at longer distances, i.e., need to refuel. Operations above 5-7000’ generally require pressurization of the aircraft. Operations at altitude require emergency supplemental oxygen in case of rapid depressurization.
+ Physiologic changes on crew are described as Time of Useful Consciousness (TUC). At 18,000 TUC = 20-30 minutes. 22,000’ = 10 min. 25,000’ = 3-5 min. 30,000’ = 1-2 minutes and 15-20 seconds at 40,000’. TUC is negatively affected by rate of ascent (think mountain climbers acclimatizing), physical activity, exertion, and fatigue.
+ Federal Aviation Regulations (FARS) require use of supplemental oxygen for flights exceeding 12,500-14,000’ if flight time is > 30 minutes and aircraft is not pressurized.
+ Jets are used for long range transport >500 miles and generally fly at higher altitudes. They require emergency supplemental oxygen for crew.
+ Patient positioning due to G Forces needs to be considered in take off / ascent of fixed wing aircraft especially jets.

Remember taking off is optional.

RECAP--
Boyle’s gas expands at altitude— think head going to explode from that sinus problem.....
Charles’ --- expansion with heat— think BLEVE;
Dalton’s --- less oxygen at altitude --- blue man group
Henry’s -- gas diffuses across membranes to equalize pressure--- flat beer--- not tasty.
Patient Considerations

Hypoxia
Non-solid organs with trapped air
Equipment: any equipment with air chambers
Barotrauma: Ascent / Descent
G-forces
Temperature
Humidity
Vibration

Crew Considerations

- Hypoxia
- Dehydration
- Noise Hearing loss
- Fatigue
  - Vibration
  - G forces
  - Third spacing
- Situational Awareness / Perception
Although visual disturbances mostly affect pilots, in single pilot operations total crew situational awareness and good crew resource management is required to minimize risk.

Visual disturbances include:
- Fascination effect – fixation on one set of visual cues with resulting failure to recognize or interpret other visual cues and total loss of situational awareness
- Prismatic effect – view of objects through windscreen with rain affecting ability to distinguish distance and height of objects
- Waterfall effect – rain cascading down a windshield causes pilot to believe he is gaining altitude while aircraft could be descending
- Flicker vertigo – rotorcraft blades similar to a strobe effect
- Engine noise is a fatigue agent in and of itself while risking long term hearing loss, fatigue, and reduced task performance. Amplitude reverberation is compartmental in any aircraft and hearing protection and visual enhancement are essential.

Care must be taken even with OTC medications (many are restricted for pilots by FAR’s) for negative physiologic effect and effect altitude resistance.

Hypoxia, fatigue, noise, and other effects of altitude all negatively affect situational awareness with potentially catastrophic results.

Reactions to visual disturbances include nausea, vertigo, convulsions, and potentially LOC.

TUC (Time of useful consciousness) is affected by:
- Engine noise is a fatigue agent in and of itself while risking long term hearing loss, fatigue, and reduced task performance. Amplitude reverberation is compartmental in any aircraft and hearing protection and visual enhancement are essential.
- Hypoxia – effect on oxygen availability, gas equalization, and gas transport through the body.
- Fatigue: Fatigue diminishes resistance to hypoxia
- Alcohol: Metabolic oxygen demand is increased with risk of hypoxia
- Nutrition status: Hypoglycemia increases risk of hypoxia
- Physical activity: e.g. doing 10 deep knee bends at 25'000 ft. w/o supplemental O2 would decrease TUC by 50%
- Noise: Noise is also associated with vertigo which is extremely dangerous for aviation operations.

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Take-Home Points

- Air medical transport requires increased attention to operating environment for both crew and patients
- Air operations, even at low altitudes, present a series of risks which must be proactively anticipated and managed
- Clinicians must have an understanding of aircraft limitations, operating characteristics, attributes, and safety equipment
- The effects of altitude physiology may be insidious, especially hypoxia, affecting both patients and air medical crew
- Crew resource management (CRM) is essential in all operations and especially essential in helicopter operations due to low altitude with limited recovery time

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