Hypobaric & Hyperbaric Conditions

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Learning Objectives:

- Explain the etiologies, patho-physiology, manifestations, complications and management of hypobaric and hyperbaric conditions.
- Explain the rationale, indications, complications, procedures and equipment associated with hyper-baric oxygen therapy.

Gas Laws

Pertinent gas laws

- Boyle's law - relationship between volume and pressure
- Henry's law - solubility of gases in liquids
- Dalton's law - law of partial pressures

Boyle's law

- For a given mass of gas at a constant temperature, the volume time the pressure equals a constant.
  - PV = Constant
  - $P_1V_1 = P_2V_2 \implies V_2 = P_1V_1/P_2$

Boyle's law

- The volume is inversely proportional to the pressure ==>
  - increasing pressure ==> decreases volume
  - decreasing pressure ==> increases volume

FYI - Click for demonstration of Boyle's law
http://www.grc.nasa.gov/WWW/K-12/airplane/boyle.html

Boyle's law

- Pressure is measured in atmospheres (Atm) or absolute (ATA)
- 1 ATA = 760 mm Hg = 14.7 psi
- A balloon contains 1.0 L at 1.0 ATA
  - at 0.5 ATA the V changes to 2.0 L
  - at 2.0 ATA, the V changes to 0.5 L

Depths, altitude & ambient pressure

- Each 33 ft underwater = 1.0 atm ==>

@ 33 ft. = 2 ATA (absolute) = 1520 mm Hg

- 19,000 ft. = 0.5 ATA = 380 mm Hg
- Mt. Everest summit = 0.33 ATA = 250 mm Hg
- 100,000 ft. approaches zero ATA

(FO2 remains 0.21)

FYI - Click for chart with altitudes and pressure
http://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html

Boyle's law

- So????
  - 6 L lung volume compressed to 3 L at 33 ft. depth
  - this would reverse on rapid ascent ==> diver holds breath during ascent and lungs burst from volutrauma
  - gas bubble increase in volume ==> 'bends'

Boyle's law

- Question - the limit to the length of a snorkel for underwater breathing is about 40 cm (16 in.) What is the basis for this limit?

Boyle's law

- Question - the limit to the length of a snorkel for underwater breathing is about 40 cm. What is the basis for this limit?
- Answer - the pressure surrounding the chest at greater depth makes the work of breathing unsustainable.
  - e.g. - at 1.0 m, the pressure is about 100 cm H2O
  - with SCUBA gear, the pressure equalizes

Henry's law

- The amount of any given gas that will dissolve in a liquid at a given temperature is a function of the partial pressure of the gas that is in contact with the liquid and the solubility coefficient of the gas in the particular liquid.

Henry's law

- Examples:
  - PaO2 x .003 = dissolved O2 ==>
  - 100 mm Hg x .003 = 0.3 mL/dL
  - 2183 mm Hg x .003 = 6.5 mL/dL

FYI - Click for more information on Henry's law
http://www.800mainstreet.com/9/0009-006-henry.html

Henry's law

- So what?
  - hyperbaric oxygen increases dissolved O2 available to tissues that are not perfused.
  - nitrogen dissolved under hyperbaric conditions produces bubbles during decompression.

Dalton's law

- The total pressure in a gas mixture equals the sum of the partial pressures of the gases.
- Alveolar air equation (clinical) -

PAO2 = FO2(Pb - 47) - (PACO2 x 1.25)

FYI - Click for Dalton's law
http://www.chm.davidson.edu/vce/GasLaws/DaltonsLaw.html

Alveolar air equation

- At 1.0 ATA a person has a normal PAO2 = 100 mm Hg (FIO2 = .21)
  - @ 6900 ft. Pb = 580 ==>
    PAO2 = .21(580 - 47) - (40 *1.25) =
    62 mm Hg
  - @ 2 ATA. Pb = 1520 ==>
    PAO2 = .21(1520 - 47) - (40 * 1.25) =
    456 mm Hg

High Altitude Physiology & Acclimatization

High altitude (HA)

- High altitude: 1500 to 3500 m (4921-11,483 ft) - high-altitude illness common with abrupt ascent to above 2500 m (8202 ft)
- Very high altitude: 3500 to 5500 m (11,483-18,045 ft) - most common range for severe high-altitude illness

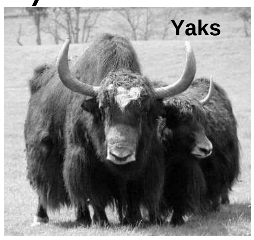
Note: ft. = meters x 3.28

High altitude (HA)

- High altitude: 1500 to 3500 m (4921-11,483 ft) - high-altitude illness common with abrupt ascent to above 2500 m (8202 ft)
- Very high altitude: 3500 to 5500 m (11,483-18,045 ft) - most common range for severe high-altitude illness
- Extreme altitude: 5500 to 8850 m (18,045-29,035 ft) - progressive deterioration of physiologic function eventually overcomes acclimatization

High altitude (HA)

- Highest permanent habitation - La Rinoconada, Peru (5100 m)
- Lhasa, Tibet (3650 m)



Living at high altitude (HA)

- Acclimatization - changes within an individual to live at HA
- Adaptation - genetic changes in populations to live at HA (generations living at HA)
  - indigenous Andeans - minimal, if any adaptation
  - indigenous Tibetans - adaptations; e.g, normal pulmonary artery pressure

High altitude alterations

- Stimulus for all mechanisms is hypobaric hypoxia
- Hypoxic ventilatory response (HPV)
  - peripheral chemoreceptors adjust ventilation for increased PaO2.
  - occurs immediately
  - capability to withstand extreme hypocapnea is one form of acclimatization

High altitude alterations

- HbO2 dissociation curve
  - hypocapnea shifts curve to left
    - increases alveolar O2 uptake
    - inhibits release of O2 to tissues
  - increased production of 2,3 DPG shifts the curve rightward, increasing release of O2 to tissues - partial compensation for hypocapnea

Pearl: One Everest climber developed a P50 = 19 mm Hg (normal = 27 mm Hg)

High altitude alterations

- Acid-base balance
  - hypocapnea ==> respiratory alkalemia
  - chronic hypocapnea causes kidneys to excrete HCO3- to balance pH - e.g.: pH = 7.45; PCO2 = 28; HCO3 = 19; base change = - 5 mEq/L
  - return to normal PCO2 causes acidemia and hyperventilation until HCO3- is retained

High altitude alterations

- Cardiovascular changes
  - heart rate and cardiac output
    - initial increase in heart rate and cardiac output
    - resting heart rate returns toward normal over time
  - pulmonary vasoconstriction ==> pulmonary hypertension

High altitude alterations

- Cerebral circulation
  - hypobaric hypoxia increases cerebral blood flow
  - hypocapnea decreases cerebral blood flow
  - cognitive impairment begins at 2500 m

FYI - click to see video of high-altitude training for pilots
http://www.youtube.com/watch?v=CptmVSXnEfc

High altitude alterations

- Hematology - hypoxia stimulates erythropoietin release, which increases RBC production
  - begins after 2 H at altitude
  - increases oxygen content

Pearl: Theoretically, genetic variations that permit survival at high altitude also improve outcomes in critical illness.

High altitude alterations

- Peripheral tissues - increased myoglobin
  - increases diffusion of O2 to muscles
  - additional reservoir for oxygen

FYI - click to download article on high-altitude physiology
http://www.ericjlee.com/Mountains/The%20Physiology%20of%20High%20Altitude.pdf

High Altitude Illness

Conditions

- Acute mountain sickness (AMS)
- High altitude cerebral edema (HACE)
- High altitude pulmonary edema (HAPE)
- Chronic mountain sickness (CMS)

FYI - click to download article on high-altitude illness
http://www.nepalinternationalclinic.com/downloads/altititude%20sickness%28seminar%29.pdf.p

AMS/HACE

- Acute mountain sickness (AMS) and high altitude cerebral edema (HACE) - same pathophysiology, different levels of severity
- Etiology - abrupt ascent to altitude >2500 m (8200 ft.)
- FYI - Vail, Colorado - 2484 m (8150 ft.)

AMS/HACE

- Risk factors:
  - rate of ascent
  - altitude for sleep
  - individual susceptibility
  - preexisting cardiopulmonary disease
  - physical exertion
  - obesity

AMS/HACE

- No gender differences in susceptibility
- Neither youth nor physical fitness confer protection

AMS/HACE

- Pathophysiology - unclear; but, elements include:
  - regional cerebral edema
  - increased intracranial pressure
  - cerebral vasoreactivity
  - cerebral vascular leakage

AMS/HACE

- Symptoms (AMS) - occur 6 - 36 H after ascent
  - headache
  - dizziness
  - disturbed sleep
  - anorexia, nausea, vomiting
  - fatigue
  - shortness of breath
  - malaise

FYI - click to see Lake Louise altitude illness scoring

http://www.high-altitude-medicine.com/AMS-LakeLouise.html

AMS/HACE

- Symptoms (HACE)
  - change in mental status; e.g., confusion
  - photophobia
  - hallucinations
- Signs (HACE)
  - ataxia (discoordination)
  - coma
  - can cause death from brain herniation

AMS/HACE & pediatrics

- Pediatric assessment
  - infant fussiness
  - appetite, vomiting
  - playful activity
  - afternoon nap

FYI - click for article on pediatric assessment for AMS/HACE
http://archpedi.ama-assn.org/cgi/reprint/152/7/683.pdf

Cardiopulmonary conditions & HA

- COPD
  - altitude worsens hypoxemia
  - altitude does NOT adversely affect lung mechanics
  - baseline PaO2 = 73 mm Hg required for 2300 m (commercial airline cabins)
  - patients with FEV_1 < 1.5 L may require supplemental O2

Cardiopulmonary conditions & HA

- Asthma
  - decreased house mite load
  - air quality can be worse; e.g., diesel exhaust and yak dung fire smoke
  - hypoxemia can cause bronchospasm
  - severe asthmatics ascend with caution

FYI - click to download article on high altitude and preexisting lung disease
http://erj.ersjournals.com/cgi/reprint/29/4/770

Cardiopulmonary conditions & HA

- Pulmonary hypertension worsens
- Patent foramen ovale (PFO)
  - predisposes to high-altitude pulmonary edema
  - worsens hypoxemia, due to right-to-left shunt

Cardiopulmonary conditions & HA

- Obesity hypoventilation - advise against high-altitude travel
- Obstructive sleep apnea - take CPAP
- Persons with migraine headaches may require slower ascent

AMS/HACE

- Prevention
  - gradual ascent (>2500 m or 8000 ft.)
    - ≤ 300 m/day
    - rest day Q 2 - 3 D
    - no further ascent for symptomatic persons

AMS/HACE

- Prevention
  - acetazolamide (Diamox) - carbonic anhydrase inhibitor
    - ventilatory stimulant
    - prevents sleep apnea
    - mimics/hastens acclimatization
    - makes carbonated beverages taste bad!! (including beer)

AMS/HACE

- Prevention
  - acetazolamide (Diamox) - carbonic anhydrase inhibitor
    - ventilatory stimulant
    - prevents sleep apnea
    - mimics/hastens acclimatization
    - makes carbonated beverages taste bad!!
  - dexamethasone (Decadron) - believed to minimize vascular leakage
  - ginkgo - is NOT effective

AMS/HACE

- Treatment
  - descent
    - > 500 m (1600 ft.)
    - problematic for back-country trekkers
  - acetazolamide (Diamox)
  - dexamethasone (Decadron)
  - theophylline (under study)

High altitude pulmonary edema (HAPE)

- Occurrence
  - $\geq$ 3000 m
  - 2 - 4 days after ascent
  - may be preceded or accompanied by AMS

HAPE

- Pathophysiology
  - hypoxia - accentuated pulmonary vascular response ==> worsened pulmonary hypertension
  - heterogeneous stress failure of pulmonary microvascular endothelium, causing fluid leak into alveoli

HAPE

- Manifestations - progressive
  - initial nonproductive cough
  - progressive dyspnea
  - tachypnea
  - tachycardia

HAPE

- Manifestations - progressive
  - production of pink, frothy sputum
  - crackles
  - severe hypoxemia
  - patchy infiltrates on chest x-ray
  - lethargy
  - coma
  - death

Click to see radiograph of HAPE
http://img.medscape.com/pi/emed/ckb/pediatrics_general/1331341-1331361-1006029-1006094.jpg

HAPE

- Susceptibility increased by:
  - male gender
  - history of HAPE
  - patent foramen ovale
  - pulmonary vascular disease

HAPE

- Prevention and treatment
  - precautions, as for AMS/HACE; e.g., graded ascent
  - pulse oximetry
    - very high altitudes
    - susceptible individuals
  - immediate descent

HAPE

- Prevention and treatment
  - precautions, as for AMS/HACE
  - pulse oximetry
  - Diamox - reverses pulmonary hypertension
  - Ca++ channel blocker; e.g., nifedipine (Procardia) - reverses pulmonary hypertension
  - phosphodiesterase inhibitor; e.g., tadalafil (Cialis) - reverses pulmonary hypertension

HAPE

- Prevention and treatment
  - Decadron - stabilizes capillary endothelium
  - inhaled beta agonists; e.g., salmeterol - high doses increase clearance of alveolar fluid
  - oxygen
  - CPAP
  - hyperbaric oxygen (portable chamber)

Chronic mountain sickness (CMS)

- AKA - Monge's disease
- Occurs in high altitude natives or long-term residents (>2500 m)
- Higher altitude ==>
  - greater prevalence
  - greater severity

Chronic mountain sickness (CMS)

- Categories:
  - primary CMS - acclimatized individuals who develop idiopathic CMS
  - secondary CMS - individuals with conditions; e.g., obesity, neuromuscular disorders, chronic lung disease

Chronic mountain sickness (CMS)

- Pathophysiologic components
  - excessive erythrocytosis (Hct >58%)
  - relative hypoventilation
  - exaggerated hypoxemia
  - pulmonary hypertension, leading to cor pulmonale

Chronic mountain sickness (CMS)

- Symptoms
  - dyspnea
  - reduced exercise tolerance
  - headache
  - anorexia
  - burning palms, plantar surfaces
  - muscle & joint pain
  - inability to concentrate
  - memory loss

Chronic mountain sickness (CMS)

- Signs
  - excessive erythrocytosis
    - Hb females >19 g/dL
    - Hb males >21 g/dL
  - severe hypoxemia, cyanosis
  - pulmonary hypertension, which may result in cor pulmonale

Chronic mountain sickness (CMS)

- Management
  - descent - permanent
  - supplemental oxygen
  - acetazolamide (Diamox)
  - phlebotomy (by Vampires?)

Chronic mountain sickness (CMS)

- Management
  - antihypertensives (studies needed):
    - Ca++ channel blockers (nefedipine)
    - phosphodiesterase inhibitors (Cialis)
    - endothelin antagonists (bosentan)
    - prostacyclins (Flolan, Ventavis)
    - nitric oxide

FYI - Click to download article on medical advice for commercial air travelers
http://www.aafp.org/afp/990901ap/801.html

Decompression Sickness & Arterial Gas Embolism

Decompression sickness (DCS)

- Rapidly decreased ambient pressure allows dissolved N2 to leave solution and form enlarged bubbles in circulation.
  - Henry's law - N2 leaves solution
  - Boyle's law - bubble enlargement

Decompression sickness (DCS)

- Contexts:
  - underwater diving - bends
  - underground construction - caisson disease
  - aircraft at altitude - loses cabin pressure - altitude DCS
  - hyperbaric chambers

FYI - click for article on history of caisson disease
http://archive.rubicon-foundation.org/dspace/bitstream/123456789/4028/1/15686275.pdf

FYI - click for joke about mine workers
Play mining joke

Decompression sickness (DCS)

- Physical factors:
  - depth (determines pressure)
  - time at depth
  - time for decompression
  - altitude; e.g., mountain lakes, caves

Decompression sickness (DCS)

- Pathophysiology - N2 bubbles cause physical and biochemical damage to tissues:
  - accumulate in joint capsules & muscles
  - obstruct blood flow to spinal cord
  - endothelial damage activates leukocytes and platelets ==>
    - inflammation
    - coagulopathy

Decompression sickness (DCS)

- Predisposing factors:
  - fatigue
  - obesity
  - dehydration
  - hypothermia
  - female gender

Decompression sickness (DCS)

- Predisposing factors:
  - increased age
  - history of DCS
  - recent alcohol use
  - flying within 24 H after diving (altitude DCS)
  - cardiovascular shunt; e.g., PFO

Decompression sickness (DCS)

- Manifestations
  - bends - pain in large joints
  - chokes - cough, substernal pain
  - skinny bends - cutaneous, itchy rash
  - lymphedema

Decompression sickness (DCS)

- Manifestations - spinal cord DCS
  - ascending paresthesia (tingling)
  - ascending paralysis
  - loss of bowel and bladder control

Arterial gas embolism (AGE)

- Pathophysiology
  - rapid decompression
  - alveolar gas expands and ruptures pulmonary vessels
  - and/or passes through PFO; then,
  - gas bubbles enter systemic circulation

Click for illustration of AGE
http://www.scubish.com/dive-reference/3/images/fig3-11.JPG

Arterial gas embolism (AGE)

- Pathophysiology
  - blockage of arteries ==> distal ischemia
  - bubbles cause cellular damage ==> leukocyte activation ==>
    - edema
    - coagulopathy ==> focal hemorrhages
    - increased permeability of blood-brain barrier

FYI - click for article on gas embolism
http://anesthesia.ucsf.edu/neuroanesthesia/residents/respdf/VenousAirEmbolism.pdf

Arterial gas embolism (AGE)

- Manifestations (sudden onset)
  - bloody froth from mouth, nose
  - marbling of skin
  - headache
  - confusion
  - sensory deficits
  - motor deficits
  - convulsions (worst case)
  - coma (worst case)
  - death (worst case)

DCS & AGE prevention

- Predive medical clearance
- Slow ascent - one-half the rate of smallest bubbles
- Breathing evenly during ascent - avoid breath holding
- No flying for 12 - 24 H after dives

FYI - click for article on scuba diving health information
http://www.ccjm.org/content/73/8/711.full.pdf+html

DCS & AGE management

- Basic life support
- Transport - low-flying craft
- Oxygen
- Recompression (hyperbaric chamber)
- Staged decompression

Hyperbaric Oxygen Therapy (HBOT)

HBOT Definition

- The patient intermittently breathes 100% O2 in a chamber pressurized to greater than 1.0 ATA

Actions (rationale)

- Increased ambient pressure
  - dissolves N2 bubbles in tissues
  - shrinks gas bubbles
  - increases PO2 in all tissues; e.g., at FIO2 = 1.0 and 3 ATA, the PaO2 = 2100 mm Hg ==> dissolved O2 = 6.3 mL/dL

Effects

- Promotes genesis of new blood vessels (speeds wound healing)
- Kills some anaerobes
- Prevents growth of species; e.g., pseudomonas
- Prevents production of clostridial alpha toxin (gangrene)

Effects

- Increases bacteriocidal effectiveness of WBCs
- Reduces WBC adhesion in reperfusion injury, preventing release of proteases and free radicals

Indications

- Strong evidence - main treatment
  - decompression sickness
  - arterial gas embolism
  - severe CO poisoning

Indications

- Strong evidence as adjunctive treatment
  - prevention and treatment of radionecrosis
  - improved skin graft and flap healing
  - clostridial tissue infections

Indications

- Some evidence
  - refractory osteomyelitis
  - acute traumatic ischemic injury
  - prolonged failure of wound healing
    - diabetic ulcers
    - thermal burns
    - crush injury
    - skin grafts
    - sternal wound infections

Indications

- Some evidence
  - severe anemia
  - autism
  - cirrhosis
  - stroke
  - intracranial abscess
  - invasive fungal infections; e.g., aspergillus
  - cerebral palsy

Complications

- Fire hazard
- Claustrophobia
- Near-sightedness (reversible)
- Barotrauma - ear damage
- Oxygen toxicity - brain and lung
- Pulmonary edema
- DCS, AGE

FYI - Click for article on HBOT
http://content.nejm.org/cgi/reprint/334/25/1642.pdf?ijkey=jUKDuJvHX0/.2

HBO chambers

- Monoplace - one patient
  - greater claustrophobia
  - portable
- Multiplace - more than one patient
  - chamber compressed with air - less fire hazard
  - O2 administered via mask, ventilators

Click to see monoplace HBO chamber
http://www.hyperbaric-oxygen-info.com/monoplace-hyperbaric-chambers.html

Click for virtual tour of multiplace HBO chamber
http://www.hyperchamber.com/virtual_chamber_tour/

Procedures

- Parameters:
  - pressure - ATAs
  - duration of sessions
  - number of sessions
- Parameters vary by condition treated
  - AGE - up to 6 ATA
  - DCI - 2-4 H @ 2.5 - 3.0 ATA
  - Wound healing - 1.5 H @ 2-3 ATA for multiple treatments

Technical points

- O2 toxicity decreased by intermittent changes to room air breathing
- Tube cuffs inflated with fluid
- IV infusion pumps lose accuracy in chambers
- Ventilator volume delivery is affected by pressure in chamber
- Sechrist 500A hyperbaric ventilator - for HBOT

Click for information on Sechrist 500A ventilator
http://classes.kumc.edu/cahe/respcared/burn/ventilat.html

Risk for personnel

- Cerebral oxygen toxicity - seizures
- DCS
- Preventive measures:
  - assessment for fitness to dive
  - adhering to decompression schedule
  - breathing O2 during decompression
  - dividing chamber time among attendants
  - avoiding flying after HBO

Summary & Review

- Gas laws
  - Boyle's law - volume and pressure
  - Henry's law - pressure and dissolved gas contents
  - Dalton's law - pressure and partial pressure

Summary & Review

- Physiologic responses - driven by hypobaric hypoxia - diminishing pressure with altitude
  - hypoxic ventilatory response
  - HbO2 curve shifts with hypocapnea and 2,3 DPG
  - acid-base balance - compensated respiratory alkalemia
  - pulmonary hypertension
  - erythropoietin - increased RBCs

Summary & Review

- High altitude illnesses
  - Acute mountain sickness
  - High altitude cerebral edema
  - High altitude pulmonary edema
  - Chronic mountain sickness

Summary & Review

- Decompression sickness
- Arterial gas embolism

Summary & Review

- Hyperbaric oxygen therapy
  - Actions - gas laws
  - Effects
  - Indications
  - Complications
  - Technical aspects - chambers, etc.
  - Risks to personnel

END

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