Atmospheric Pressure Problems related to Spacesuits

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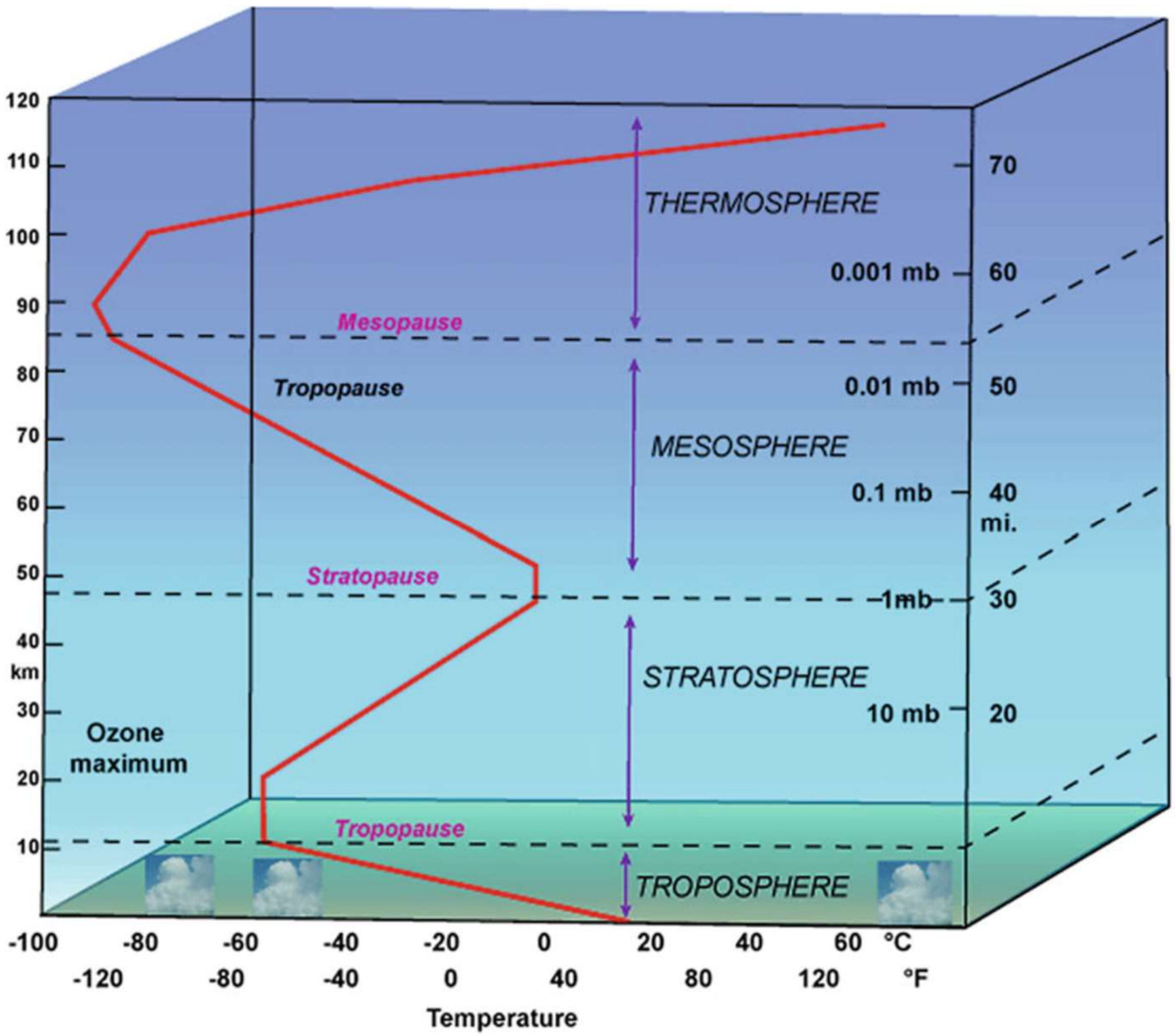
U.S. SKC Program Spacesuit Medical Series

Learning Objectives

Understand the relationship between atmospheric pressure and various gas disorders as they relate to human survival in space

Comprehend the distinction between evolved gas disorders (decompression sickness), trapped gas disorders (barotrauma), and vacuum exposure (ebullism)

Temperature and Pressure Environment from Sealevel to 120 Km



Clark JB. (2020) The Space Environment: An Overview. In: Young LR. Sutton JP. (eds) Handbook of Bioastronautics. Springer, Cham. https://doi.org/10.1007/978-3-319-10152-1_127-1

Time to Death without:

Atmospheric pressure – seconds

Oxygen - minutes

Thermal Protection - hours

Water - days

Food – weeks to months

Gravity – unknown but greater than years

Atmospheric Entry Human Health Threats

Entry Phenomenon	Physical Characteristics	Altitude Range	Biologic Effect	Countermeasure
Plasma	Ionized molecular O2	> 130,000 Feet	Chemical / Thermal burn	Thermal Protection System
Excessive Acceleration Gradients	Delta G (dG/dT) x, y, z linear/ angular planes	Below Entry Interface (400K)	Organ/ Skeletal Damage, Body Fragmentation	Crew Compartment Stability System, Axial Restraint System
Shock Shock Interaction	Blast Wave Pressure	NA/ supersonic speeds	Organ Damage, Body Fragmentation	Aerodynamic Design, Crew Compartment Integrity
Dynamic Heating	C	> 150,000 feet	Thermal Burn	Thermal Protection System
Dynamic Pressure	Q		Organ/ Skeletal Damage, Body Fragmentation	Crew Protection System
Atmospheric Pressure	Atmosphere Absolute (ATA)	> 63,000 feet (< 0.06 ATA)	Tissue water vaporized to gas resulting in ebullism	Pressure Vessel, Pressure Suit, Pressure Breathing Mask
Atmospheric Pressure	Atmosphere Absolute (ATA)	> 18,000 feet (< 0.5 ATA)	Evolved tissue nitrogen resulting in decompression sickness (DCS)	Pressure Vessel, Pressure Suit, Pressure Breathing Mask
Pressure Differential	Delta pressure (dP)		Barotrauma in gas filled spaces (lung, ear, GI) resulting in arterial gas embolism	Pressure Vessel, Pressure Suit
Oxygen Partial Pressure	ppO2	> 10,000 feet	hypoxia and asphyxiation	Pressure Vessel, Pressure Suit, supplemental Oxygen
Intrusion of Habitable Space	Physical Trauma	NA	Fatal or severe organ damage due to penetration	Crew Compartment Protective System
Terrain Impact	Delta G (dG/dT) x, y, z linear planes	Surface	Injury due to Rapid Deceleration	Parachute, Lifting body, Airbag, Braking Rocket

Loss of Signal: Aeromedical Lessons Learned from the STS-107 Columbia Space Shuttle Mishap, Stepaniak PC, Lane HW (eds). Washington DC: U.S. Government Printing Office, NASA/SP-2014-616, ISBN: 9780160923876, page 133.

Barometric Pressure Related Problems

Decompression Illness (DCI) aka DCS

with pressure reduction, evolved gas bubble from dissolved nitrogen can cause pain, pulmonary or nervous system damage within minutes to hours

Barotrauma

expansion of gas filed cavities, worst situation is pulmonary over-inflation with collapsed lungs, arterial gas embolism within seconds

Ebullism

gas evolved from water (vapor pressure) below 47 mm Hg
severe lung damage within minutes

Relevant Gas Laws

Henry's Law: amount of dissolved gas in a liquid will decrease if the pressure around the liquid decreases

DECOMPRESSION SICKNESS (evolved gas disorder)

When pressure is reduced, gas comes out of solution in the form of bubbles

Nitrogen bubbles in blood and tissues cause pain, tingling, pulmonary chokes, brain and spinal cord damage

Boyle's Law: gas volume is inversely proportional to pressure

BAROTRAUMA (trapped gas disorder) As you ascend, pressure goes down and volume goes up, causing gas-expansion in digestive system, teeth cavities, sinuses, ears, lungs

Pressure Related Problems

Decompression Sickness

gas evolved into tissues from dissolved nitrogen

joint pain, nervous system damage within hours

Barotrauma

expansion of gas filed cavities resulting in pulmonary over-inflation

collapsed lungs, arterial gas embolism within seconds

Ebullism

gas evolved from water (vapor pressure) below 47 mm Hg

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Decompression Sickness (DCS) now called Decompression Illness

The manifestation of symptoms caused by the evolution of inert gas bubbles from dissolved nitrogen in body fluids and tissues following reduction in ambient pressure

Hyperbaric (caisson disease, diving) DCS – going from increased pressure at depth back to the surface

Hypobaric (altitude) DCS – going from increased pressure to decreased pressure ascending in altitude

Altitude Decompression Sickness (DCS)

Altitude (sub-atmospheric) DCS

- At sea level (1 atmosphere) tissues and blood are supersaturated with nitrogen
- When pressure is reduced (altitude increased) nitrogen comes out of solution to form bubbles
- Depending on bubble location, DCS can have multiple manifestations that may very in location, intensity, and time

Type I DCS – Limb or Joint Pain (bends), cutaneous (skin) manifestations such as itching and rash (niggles)

Type II DCS – Neurologic (headache, weakness, paralysis), cardiopulmonary “chokes”

Altitude Decompression Sickness (DCS)

Limb Pain - Typically joint or muscle pain (70% - 84% of all altitude DCS symptoms) most common DCS symptom

Skin - Mottling, pins and needles, tingling, prickling (about 13% of all altitude DCS symptoms) second most common DCS symptom

Neurologic - Cold sweat, dizziness, edema, inappropriate or sudden onset of fatigue, headache, light headedness, loss of consciousness, motor and/ or sensory loss, nausea, tremor (shakes), vertigo (1% - 8% of all altitude DCS symptoms)

Respiratory (pulmonary) - Cough, dyspnea (difficult or labored breathing), substernal distress (tightness and/or pain in chest, especially during inspiration) (3% of all altitude DCS symptoms)

Altitude Decompression Sickness (DCS)

Primary Altitude DCS risk factors:

- Altitude: rare below 18,000 ft
- Duration of altitude exposure: usually at least five minutes at altitude, longer time = higher incidence
- Activity Level at altitude
- Denitrogenation/ Oxygen Prebreathe reduces incidence
- Flying within 24 hours after SCUBA diving

Lesser factors

- Rate of ascent
- Individual Factors (age, body build (fat has more nitrogen), general health, prior injury, individual susceptibility)

Gas Bubbles in Fascial Space

Pilmanis AA, Clark JB. "Decompression-Related Disorders." Chapter 16 in *Principles of Clinical Medicine for Space Flight* 2nd edition Barratt MR, Baker ES, Pool SL, eds. New York: Springer-Verlag (2019): 481-518.

18 Fatal Altitude DCS Cases

17 fatal altitude DCS cases 1943 -1958 (Fryer 1969)

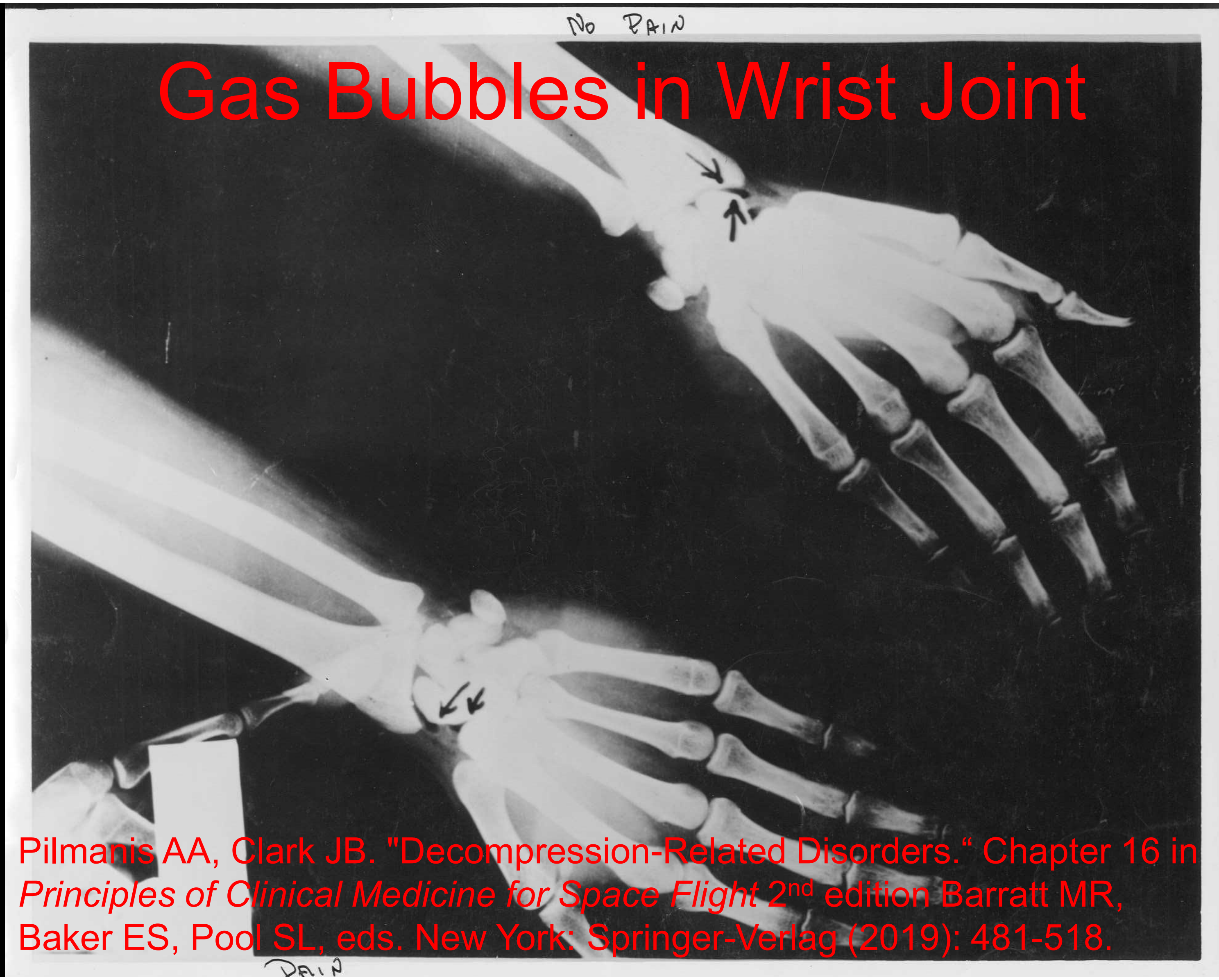
- 59% altitude chamber/ 41% in flight
- Age: mean 31.2 years (range 22 to 50 years)
- Weight: mean 197 lbs. (range 165 to 235)
- Mean time to death: 21.5 hours (range: 5.5 to 71 hours)
  - Minimum altitude: 22,000 feet/ 22 min
  - Minimum duration: 35,000 feet/ 8 min
  - Average: 32,500 feet/ 56 min
- Clinical presentation at altitude
  - Chokes: 41%
  - Limb pain, abdominal pain, CNS: 29%
- Clinical Factors:
  - Pulmonary congestion/ edema: 82%
  - Pulmonary fat emboli: 50%
  - Patent foramen ovale: 45%

No Oxygen Prebreathe

Latest DCS Fatality (Neubauer 1988)

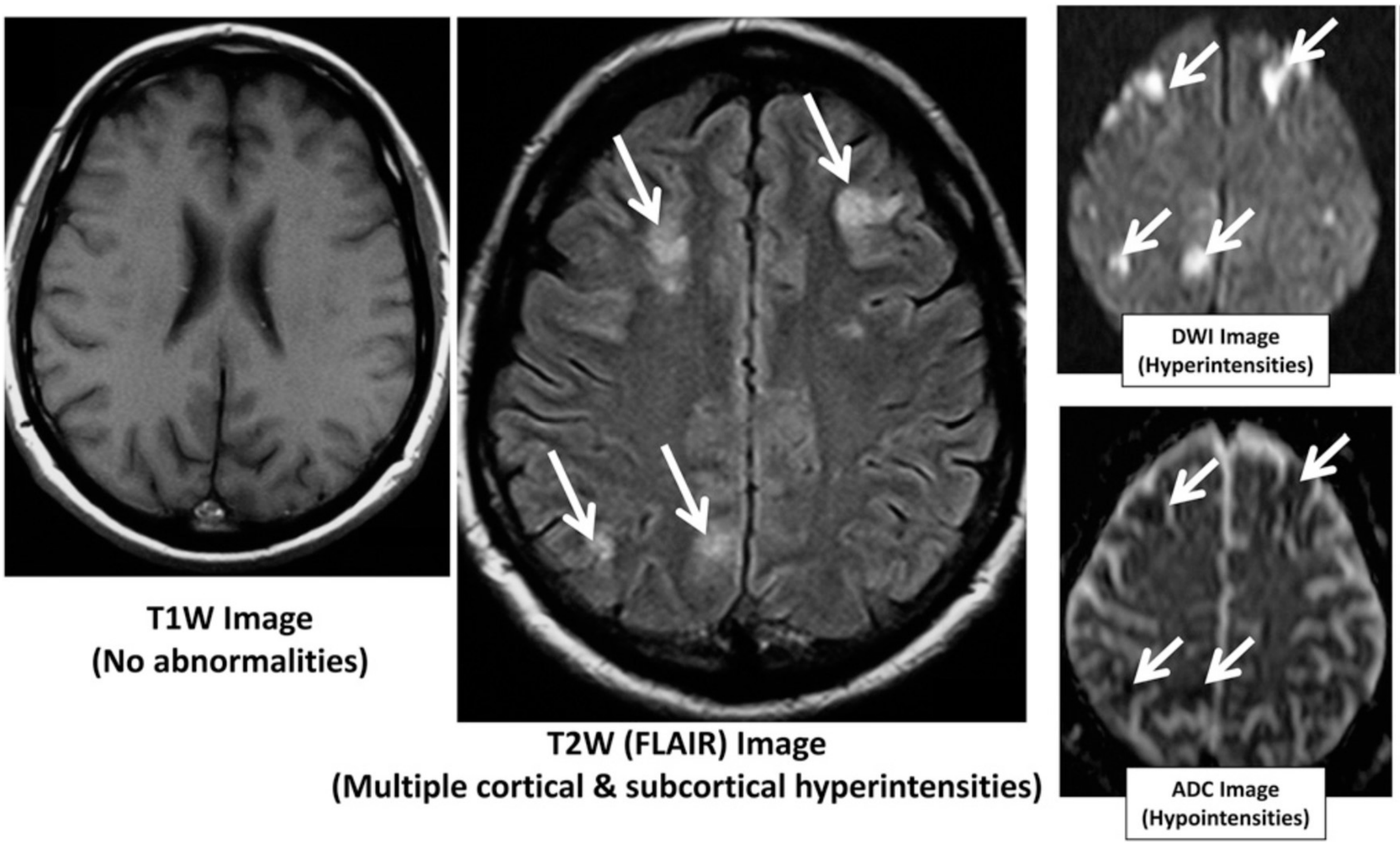
- 51 year old obese male pilot had dyspnea with cabin pressure loss at 28,000 feet for 30 minutes
  - Treated with Hyperbaric Oxygen, death 7 hours after symptom onset

Gas Bubbles in Wrist Joint



Pilmanis AA, Clark JB. "Decompression-Related Disorders." Chapter 16 in *Principles of Clinical Medicine for Space Flight* 2nd edition Barratt MR, Baker ES, Pool SL, eds. New York: Springer-Verlag (2019): 481-518.

Acute brain lesions in U-2 pilot with severe neurological DCS



Jersey SL, Jesinger RA, Palka P. Brain magnetic resonance imaging anomalies in U-2 pilots with neurological decompression sickness. Aviat Space Environ Med 2013; 84:3–11.

Pressure Related Problems

Decompression Sickness

gas evolved into tissues from dissolved nitrogen

joint pain, nervous system damage within hours

Barotrauma

expansion of gas filed cavities resulting in pulmonary over-inflation

collapsed lungs, arterial gas embolism within seconds

Ebullism

gas evolved from water (vapor pressure) below 47 mm Hg

severe lung damage within minutes

Pressure Changes with Altitude

As atmospheric pressure decreases, the air volume increases

Boyle's Law – pressure inversely related to volume

Dry Gas Volume Expansion

- At 18,000 feet 2X
- At 28,000 feet 3X
- At 34,000 feet 4X
- At 39,000 feet 5X
- At 43,000 feet 6X

Trapped Air Barotrauma

During atmospheric pressure reduction there are several places in the human body where air can get trapped and not vent outside the body, such as the ear, sinuses, stomach and intestines and lungs.

As atmospheric pressure reduction occurs the gas can expand in body tissues resulting in injury

The most serious form is expansion of gas within the lungs

Most Serious Type of Barotrauma is in the Lung

Pulmonary Over Inflation Syndrome

Intrapulmonary pressure differential of 1.5-1.9 psi (80-100 mm Hg) over 0.1 to 0.2 sec may result in alveolar rupture

This is the most serious form of barotrauma

Collapsed lungs (pneumothorax)
Air in pericardial sac (pneumocardium)
Air under the chest (pneumomediastinum)
Air under the skin (subcutaneous emphysema)
Air in arterial blood vessels (arterial gas embolism or AGE)
Cerebral Arterial Gas Embolism (CAGE) is the most serious

Depressurization Lung Damage Thresholds

Pressurized Volume to Leak Area Ratio (V/A Ratio) m^3/m^2	Injury Potential
32.3	1966 NASA case, no pulmonary injury
15	No animal fatalities
3.3	Fatal in some animals
1.1 – 1.2	50% fatal (animal data) LD_{50}
0.12	100% fatal (animal data)

The higher the Pressurized Volume to Leak Area Ratio the less potential for lung damage and death

Roth EM, "Rapid (Explosive) Decompression Emergencies in Pressure-Suited Subjects," NASA CR-1223, 1968.

Pressure Related Problems

Decompression Sickness

- gas evolved into tissues from dissolved nitrogen
  - joint pain, nervous system damage within hours

Barotrauma

- expansion of gas filed cavities resulting in pulmonary over-inflation and lung rupture
  - collapsed lungs, arterial gas embolism within seconds

Ebullism

- **gas evolved from water (vapor pressure) below 47 mm Hg**
  - **severe lung damage within minutes**

Human Exposures To Ebullism (RED = fatal)

Jim Henry put hand in vacuum glove box – 1940s

Jim McBarron lost visor in vacuum chamber test - 1959

Joe Kittinger lost right glove pressure on Excelsior III – 1960

Russian Volga stratospheric freefall test, helmet visor cracked at 86,000 feet under parachute, fatal - 1962

Jim LeBlanc exposed to 120,000 ft in NASA JSC vacuum chamber test when space suit umbilical disconnects - 1966

F-104 zoom flight, pressure suit glove came off, aircraft crashed - 1968

Soyuz 11 crew died from cabin pressure leak – 1971

Industrial accident in vacuum chamber - 1981

STS 107 crew perished when cabin lost pressure, suits not configured for immediate vacuum exposure – 2003

High Altitude Human Vacuum Experience

Human survival following accidental decompression

In 1966 a space suit test subject had near instantaneous exposure to altitude of 120,000 feet.

He recalled the saliva boiling off his tongue as he passed out, and regained consciousness as the chamber reached 14,000 feet.

He suffered no neurological sequelae and was not hospitalized.

Roth EM, "Rapid (Explosive) Decompression Emergencies in Pressure-Suited Subjects," NASA CR-1223, 1968.

High Altitude Human Vacuum Experience

Accidental Decompression

In 1982 a technician was decompressed to greater than 74,000 feet (22,555 m)

He was above 63,000 feet for 1 to 3 minutes

Bilateral pnuemothorax and unconscious

Recompression therapy 5 hours after exposure

awake and alert at 24 hours, extubated at day 5

Normal neurologically at 1 year

Kolesari GL, Kindwall EP . Survival following accidental decompression to an altitude greater than 74,000 feet (22,555 m) . Aviat Space Environ Med 1982 ; 53 : 1211 – 4 .

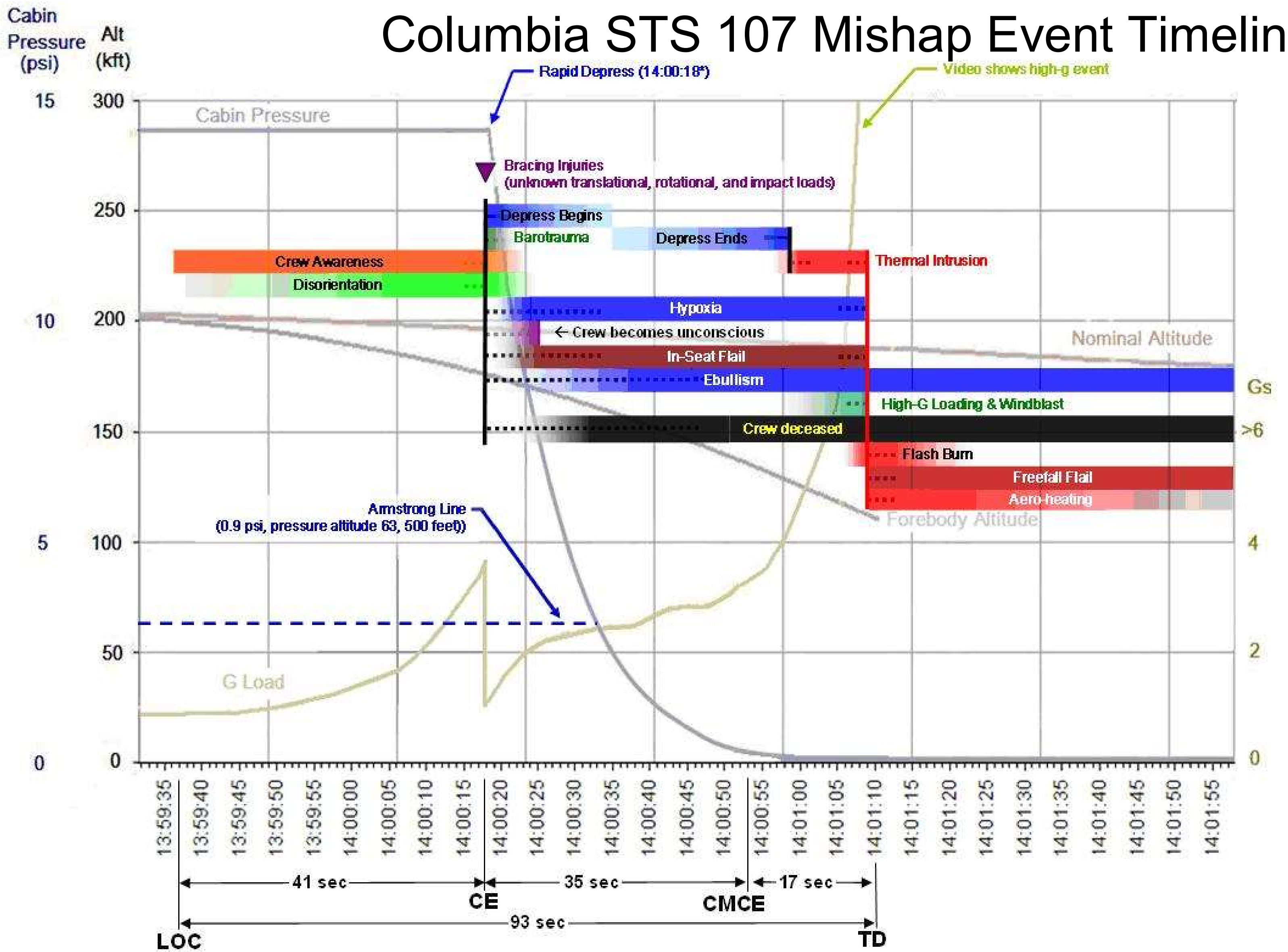
Soyuz 11 Crew

NASA System Failure Case Study-2010-09-09-
Descent into the Void Soyuz 11 Depressurization

Soyuz 11 Cabin Depressurization during Descent Phase

- First crew to occupy a space station (Salyut 1 for 22 days)
- Launch and entry pressure suits were not used
- During reentry a pressure equalization valve opened early from vibrations (module separation pyrotechnics)
- Crew unsuccessfully attempted to close the isolation valve (stem valve required multiple turns)
- Cabin fully depressurized in 212 seconds
- Basic resuscitation provided post landing, crew not resuscitated

Columbia STS 107 Mishap Event Timeline



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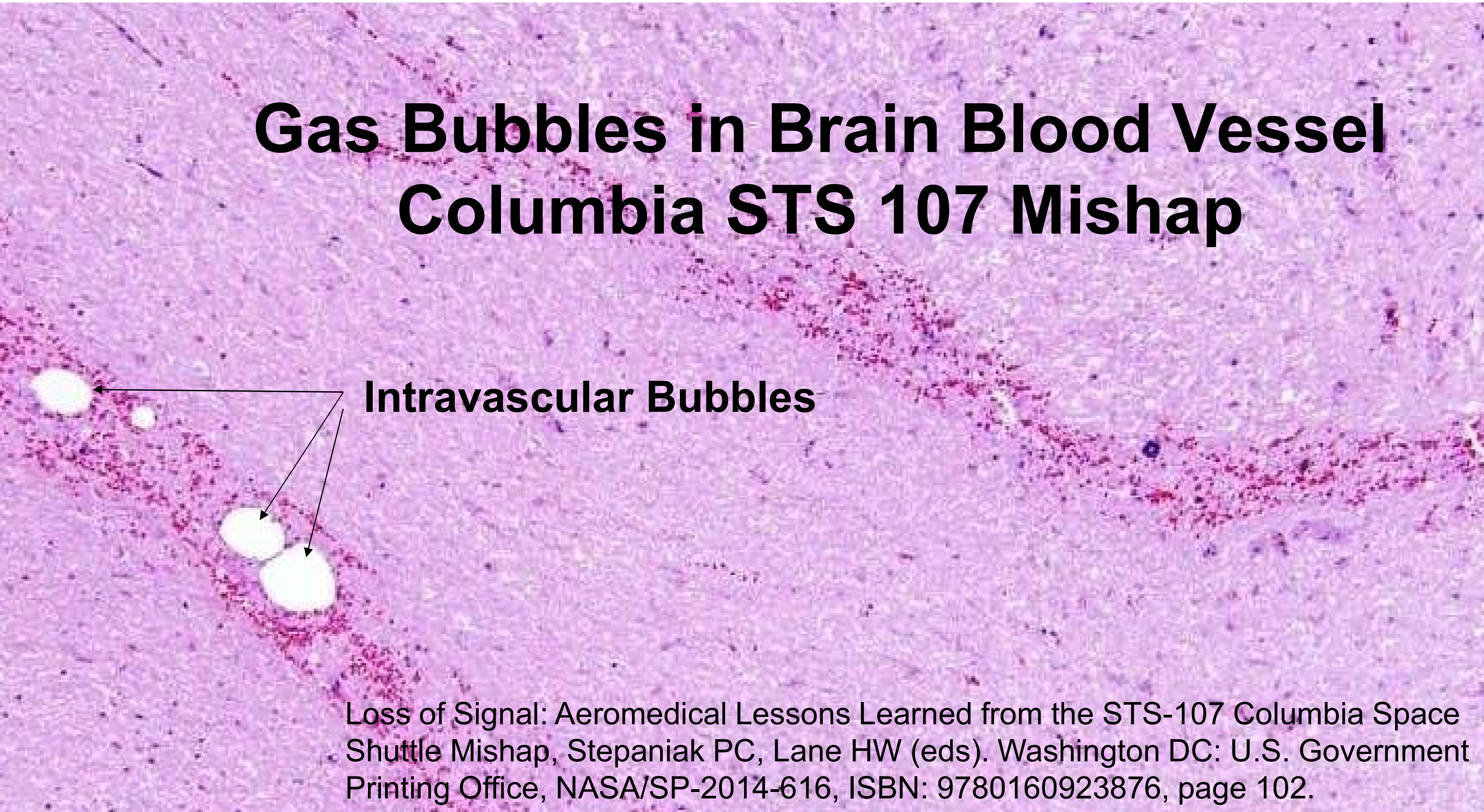
Gas Bubbles in Brain Blood Vessel
Columbia STS 107 Mishap



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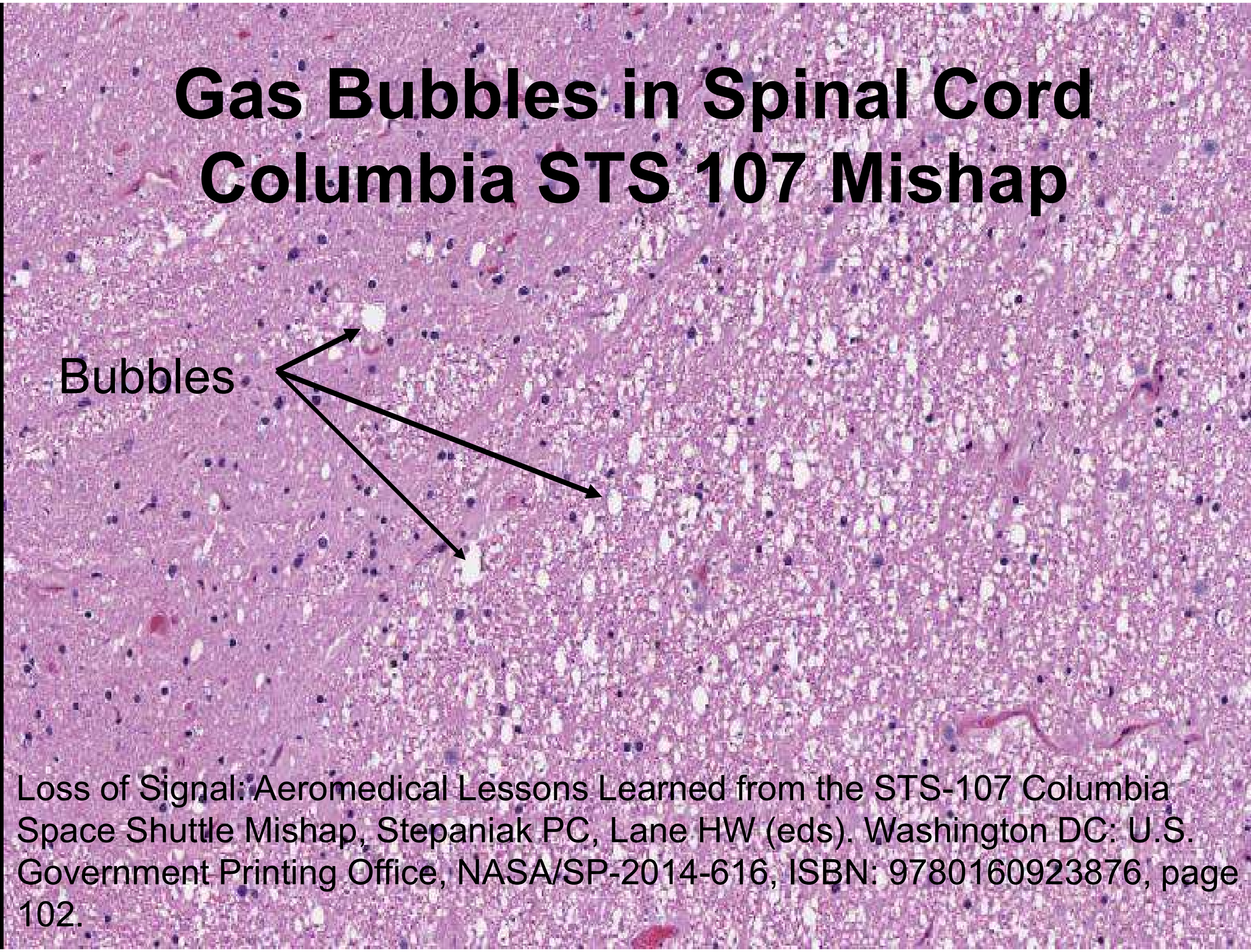
Gas Bubbles in Spinal Cord
Columbia STS 107 Mishap



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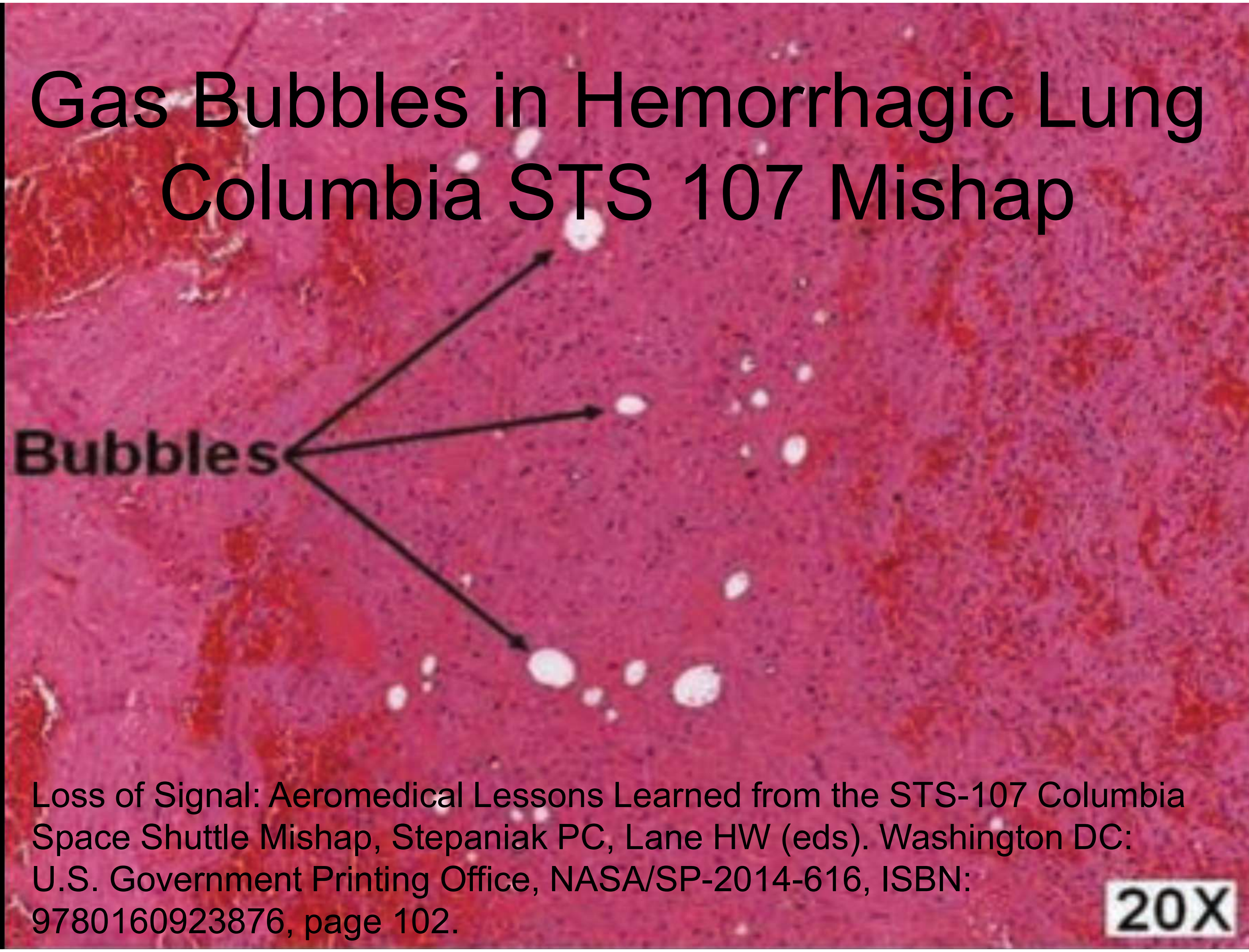
Gas Bubbles in Hemorrhagic Lung Columbia STS 107 Mishap



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Definition of Ebullism

The effervescent evaporation of body fluids at barometric pressure at or below the saturated vapor pressure at body temperature

Synonym is hypobaric boiling

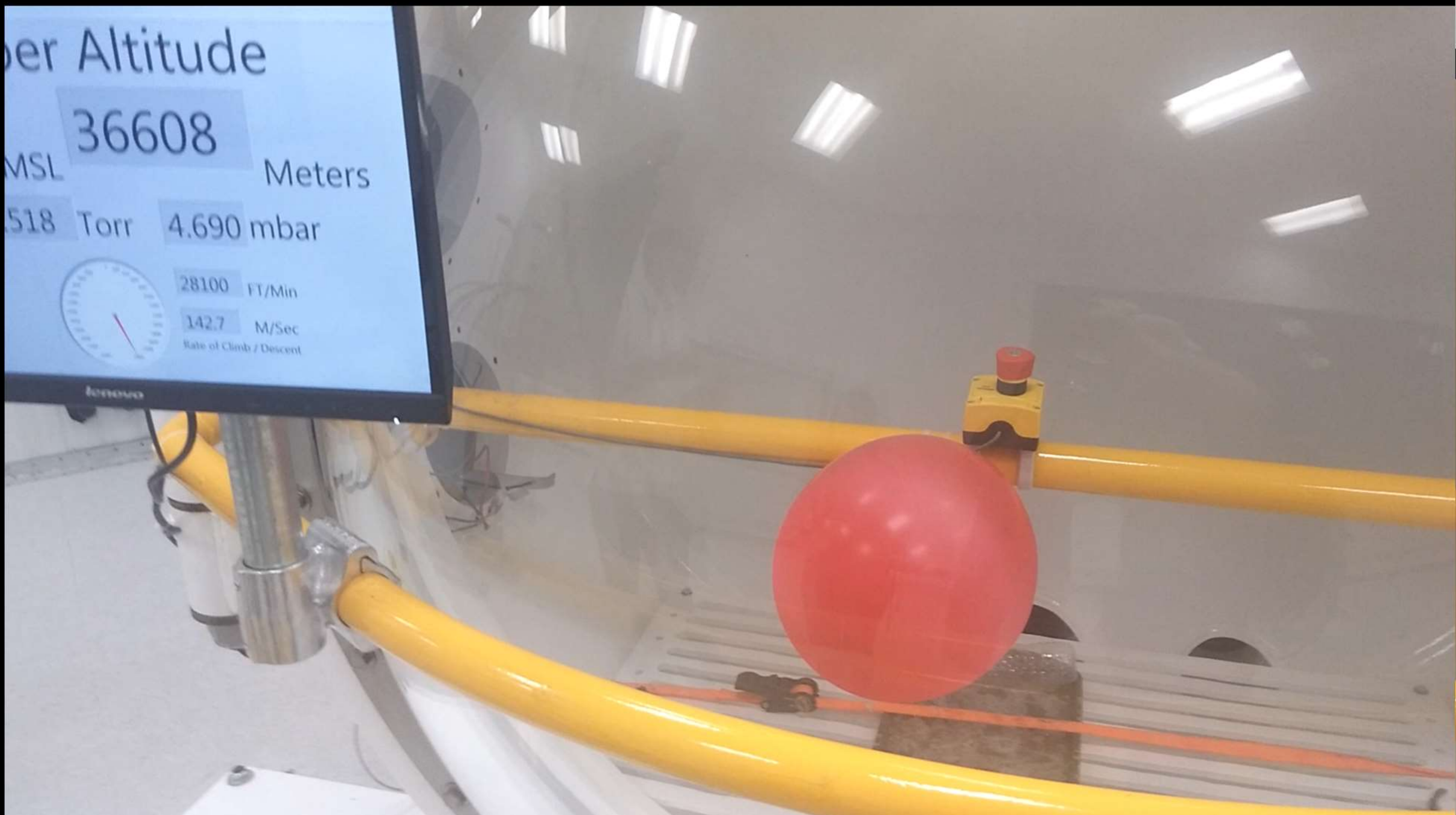
47 mm Hg/ .91 psi (vapor pressure of water at 37 deg C)

Equivalent to 63,000 feet (19,200 meters) altitude

Armstrong Line is really Armstrong Band

Recent insight concerns higher altitude 115-120K feet (0.09 psi/ 4.5 mmHg) where H_2O exists in all three states (solid, liquid, gas) called the water triple point

Midland Altitude Chamber Complex


Altitude
36608
MSL
Meters
Torr
4.690 mbar
28100 FT/Min
142.7 M/Sec
Rate of Climb / Descent


Space Ice
JB Clark Photo 2016

Consequences of Humans Subjected to Ebullism

Large bubbles of gas form within the blood vessels, obstructing blood flow

Pockets of gas are seen in subcutaneous tissues within 2 to 3 seconds, within the abdominal cavity after 7 - 10 seconds, and within the heart and great vessels after 20 seconds. The rapid expansion of bubbles in the chest cavity (vapothorax) impairs heart and lung function

Considered to be rapidly fatal, with consciousness being lost within seconds and death within 3 - 5 mins

Medical Treatment for Ebullism

Based on the pulmonary pathophysiology of ebullism, and the similarity to acute respiratory distress syndrome, critical care experts suggested the following approach:

High Frequency Percussive Ventilation

Murray DH, Pilmanis AA, Blue RS, Pattarini JM, Law J, Bayne CG, Turney MW, Clark JB.

Pathophysiology, prevention, and treatment of ebullism. *Aviat Space Environ Med* 2013; 84(2):89-96.

Summary

Ambient pressure reduction can lead to injury or death from bubble related disorders, depending on altitude level, duration of exposure, and rate of decompression

Bubble related disorders may be from evolved gas (decompression sickness), trapped gas (barotrauma) and/ or water vaporization (ebullism)

Bubble related disorders can occur concurrently

Prebreathing oxygen reduces risk of decompression sickness and improves survival

Survival following exposure to vacuum is possible

Humans survival in vacuum is based on exposure duration and altitude

Lung damage is primary factor in survival from vacuum exposure

References

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