



AEROSPACE INFORMATION REPORT

AIR825™/2**REV. A**

Issued 2007-07
Reaffirmed 2017-11
Revised 2023-12

Superseding AIR825/2

(R) Effects of Acute Altitude Exposure in Humans:
Requirements for Physiological Protection

RATIONALE

AIR825/2 has been updated to reflect the latest developments in the consequences of altitude exposure in aviation: mild hypoxia and exposure to altitude after rapid decompression, taking in account the flight altitude and the decompression rate.

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1. SCOPE

The intent of this SAE Aerospace Information Report (AIR) is to describe the effects of the environmental changes on human physiology and the protection required to avoid negative consequences resulting from altitude exposure. A brief presentation of basic terms and considerations required to discuss the topic of human physiology at altitude is followed by an overview of the cardiovascular and respiratory systems. Issues specifically related to human exposure to altitude are discussed. Hypoxia, hyperventilation, barotrauma, and decompression sickness (DCS) are each addressed. One goal of this AIR is to demonstrate the necessity of oxygen use for prevention of physical and psychological problems, or loss of consciousness in an aircraft. This should provide a clear understanding as to why the use of supplemental oxygen is required for flight crew and healthy passengers at altitude greater than 10000 feet (3048 m).

1.1 Purpose

The purpose of this AIR is to describe the physiological needs for protection of humans against altitude in aviation.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR1069 Crew Oxygen Requirements Up to a Maximum Altitude of 45,000 Ft.

AIR6829 Oxygen Considerations for High Elevation Airport Operations (HEAO)

AS861 Minimum General Standards for Oxygen Systems

AS8010 Aviator's Breathing Oxygen Purity Standard

2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR Part 23 Airworthiness Standards: Normal, Utility, Acrobatic, and Commuters Category Airplanes

14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes

TSO-C99 Flight deck (sedentary) Crewmember Protective Breathing Equipment

TSO C116a Crewmember Portable Protective Breathing Equipment

2.1.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany, Tel: +49 221 8999 000, www.easa.europa.eu.

CS-23 Certification Specifications and Acceptable Means of Compliance for Normal, Utility, Acrobatic, and Commuters Category Airplanes

CS-25 Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes

ETSO-C99 Protective Breathing Equipment

ETSO-C116a Crewmember Portable Protective Breathing Equipment

Commission regulation (EU) n° 965/2012: Technical requirements and administrative procedures related to air operations

2.1.4 NATO Publications

Copies of these documents are available online at <https://www.sto.nato.int/publications/>.

STANAG 3198AMD Physiological Requirements For Aircraft Oxygen Equipment And Pressure Suits.

2.2 Other Publications

2.2.1 General Publications

Gillies, J.A. (1965). "A textbook of aviation physiology." *Pergamon Press*.

Gradwell, D. and Rianford, D. (2016). "Ernsting's aviation and space medicine 5E." *CRC Press*. ISBN 9781444179941.

U.S. Air Force. (1950). "German aviation medicine World War II." *Surgeon General, U.S. Air Force*.

FAA. (n.d.). "Introduction to aviation physiology." Available at https://www.faa.gov/pilots/training/airman_education/media/IntroAviationPhys.pdf.

2.2.2 Books or Papers

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- [2] Bert, P. (1943). "Barometric pressure," translated by Hitchcock, M.A. and Hitchcock, F.A., *College Book Company*.
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- [4] Gaume, J.G. (1970). "Factors Influencing the Time of Safe Unconsciousness (TSU) for Commercial Jet Passengers Following Cabin Decompression." *Aerosp Med*, 41(4):382-385.
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- [11] Violette, F. (1954). "Les Effets Physiologiques des Décompressions Explosives et Leurs Mécanismes." *Rev. Méd. Aéro.*, 223-271.
- [12] Wenzel, J., Luks, N., Plath, G., Wittkowski, M. (2009, May 8-12). "Rapid decompression from 8 to 45 kft in 20 seconds." SAE-A10 Spring meeting, Denver, CO.
- [13] Wenzel, J., Luks, N., Plath, G., Wittkowski, M., Bloch, N., Deutscher, W. (2011). "Rapid decompression from 8 to 45 kft in 20 seconds initially breathing air: experimental results from 10 human trials." *Aviation, Space, and Environmental Medicine*, 87(3):249-250, abstract #127.

2.3 Definitions

BAROTRAUMA: Injury caused by pressure: most commonly referencing injury to the walls of the Eustachian tube and the ear drum due to the difference between atmospheric and intratympanic pressures, and

DECOMPRESSION SICKNESS (DCS): Related to an excess of nitrogen in the body tissues.

HYPERVENTILATION: An excessive rate of ventilation with ultimate consequences on acido-basic equilibrium,

HYPOXIA: An insufficient supply of oxygen to the tissues,

3. GENERAL

3.1 Units

In any serious discussion of altitude exposure, quantitative descriptions are required. The variables of primary interest being altitude, pressure, and temperature, a variety of units are commonly used with each of these parameters. Table 1 presents conversion factors for some of the most frequently used units for each of these parameters. In addition, the term Flight Level (FL) is commonly used in aeronautical practice. It is a valid reference for discussions of physiological limitations since it provides a common reference for the effects of pressure changes on the human body. It is, however, a valid means to determine absolute altitude with reference to sea level. Flight level is defined as the conventional altitude, expressed in feet, divided by 100 (for instance: FL 300 is 30000 feet, with pressure altitude equal to 301.5 hPa or 226.1 mm Hg).

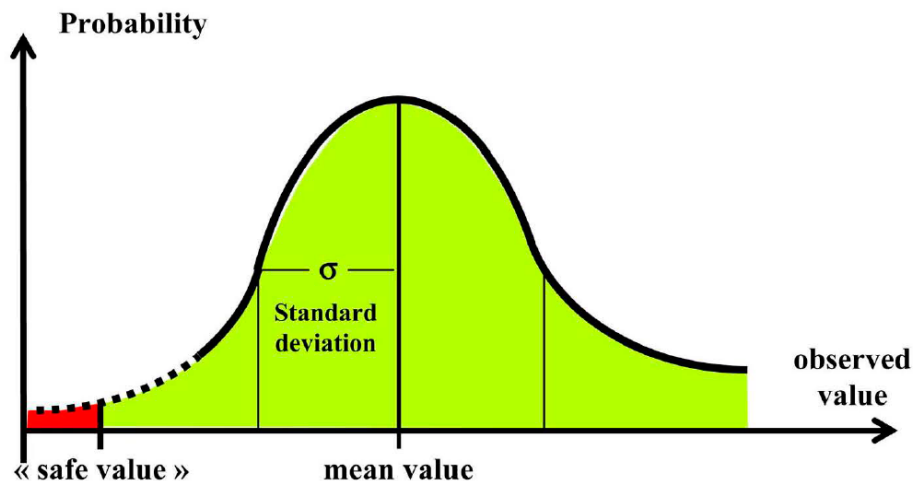
The units of volume, in the metric system is dm^3 and the units of flow in the metric system is $\text{dm}^3/\text{s}^{-1}$. But the usual designation is the liter or liter per unit of time. In this text, we'll use the liter (L), the liter per minute (L/min), and the liter per second (L/s).

Table 1 - Common conversion factors

Pressure to	mm Hg	In H ₂ O	hPa	psi
From	Multiply by			
mm Hg	1	0.5353	1.3333	0.0193
in H ₂ O	1.8683	1	2.4909	0.0361
hPa	0.7501	0.4014	1	0.0145
psi	51.7149	27.7000	68.9476	1
Length to	Feet		Meters	
From	Multiply by			
Feet	1		0.3048	
Meters	3.281		1	
Volume: 1 l = 1 dm ³				
Temperature				
Fahrenheit (°F)	Celsius (°C)		Kelvin (K)	
°F = 9/5 °C + 32	°C = 5/9 (°F - 32)		K = °C + 273.15	

3.2 Mean Values and Safe Values

In many instances, data will be presented in this paper to demonstrate the concepts and issues being discussed. Confusion could result regarding the interpretation of these numbers if the differences between mean and safe values are not recognized. The mean of a set of data is the average value of all the observations. Usually, a measure of variability, such as standard deviation, among observations is also calculated. These measures are most meaningful when the observations are distributed in a manner that is referred to statistically as normal. For example, if one were to measure the height of 1000 individuals, the distribution of heights between the tallest and shortest individual would be expected to resemble that presented in Figure 1. Most biological data can be described or summarized in this manner. The sections of this AIR which address the fundamental functioning of human body will often utilize means and standard deviations to describe responses.

**Figure 1 - Gauss curve, mean and safe values**

NOTE: This curve describes the probability to observe a given value. The number of subjects, which are above this value, is in relation with the area under the curve. "Safe value" must leave ideally no subjects under the curve at the left of this value.

When the topic of discussion is the adaptive and performance limits of humans at altitude, a different perspective and analysis must be utilized. The object is flight safety. Therefore, statistically unusual responses must be considered. The part of this AIR which discusses data directly related with aviation safety will use safe data. Regulatory bodies often utilized safe data as the basis for their requirements. Although safe data can be described in statistical terms, mean data and safe data are not necessarily the same across the human population as a whole. For instance, subpopulations such as military people versus older passengers on commercial airline flights may be characteristically different for a given response.

4. ATMOSPHERE

As a biological species, humans are predominantly aerobic (i.e., dependent upon oxygen for metabolic energy production), requiring relatively specific environmental conditions for survival and comfort. Due to intelligence, humans have developed technologies that allow them to live in an extreme range of environments. Included within this range are the atmospheric changes associated with ascent to altitude in aircraft. If not controlled and regulated, the environmental changes associated with flying will result in physical and mental performance deficits that represent a serious threat to survival.

4.1 Atmospheric Pressure

Barometric pressure (P_B) decreases with altitude in an exponential relationship (see Figure 2). Just a few key values are required to show how fast the atmospheric pressure decreases as the altitude increases:

- Standard value at sea level (P_{B0}): 1013 hPa (760 mm Hg)
- $P_{B0}/2$, i.e., 506 hPa (380 mm Hg) at about 5500 m (18050 feet)
- $P_{B0}/4$, i.e., 253 hPa (190 mm Hg) at about 10300 m (33800 feet)
- $P_{B0}/10$, i.e., 101.3 hPa (76 mm Hg) at about 16150 m (53000 feet)
- $P_{B0}/100$, i.e., 10 hPa (7.6 mm Hg) at about 30500 m (100000 feet)

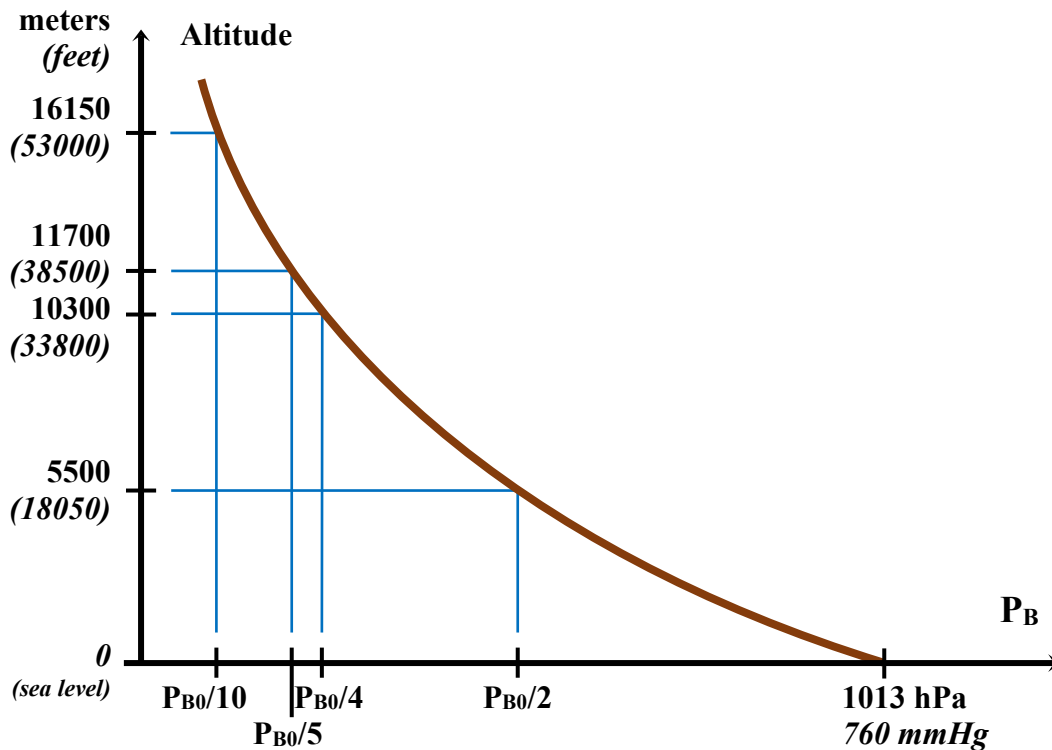


Figure 2 - Graph indicating atmospheric pressure (P_B) in relation to altitude

4.2 Temperature

The temperature of the atmosphere decreases as altitude increases, up to about 37000 feet (11300 m) where temperature reaches a mean value of approximately -56.5°C (-69.7°F , 216.7 K). Above this altitude, for all flight levels used in aeronautics, the temperature remains constant (Figure 3).

4.3 The Composition of the Atmosphere

For the majority of gases, the composition of the atmosphere is constant at all the flight levels operated in aeronautics. The primary exceptions are water vapor and carbon dioxide. Table 2 lists the components normally found in the lower layers of the atmosphere. Ozone is situated mainly between 50000 feet and 150000 feet (15 km and 50 km), with a maximum at 100000 feet (30 km).

For human respiration, the most important element in the atmosphere is oxygen. On a percentage basis, oxygen makes up 20.95% of the gas in the air. This percentage is important in that it is used in calculating the partial pressure of oxygen (P_{O_2}). It is the P_{O_2} that provides the force to drive oxygen into the body. Since the percentage of oxygen in the air remains constant, the P_{O_2} varies in direct proportion with the atmospheric pressure. The gas pressures, partial or total, are most important when considering physiological parameters. The reason is the gas partial pressure will determine the extent to which the gas will be found in the body. Areas of the body containing gases can be divided into three categories:

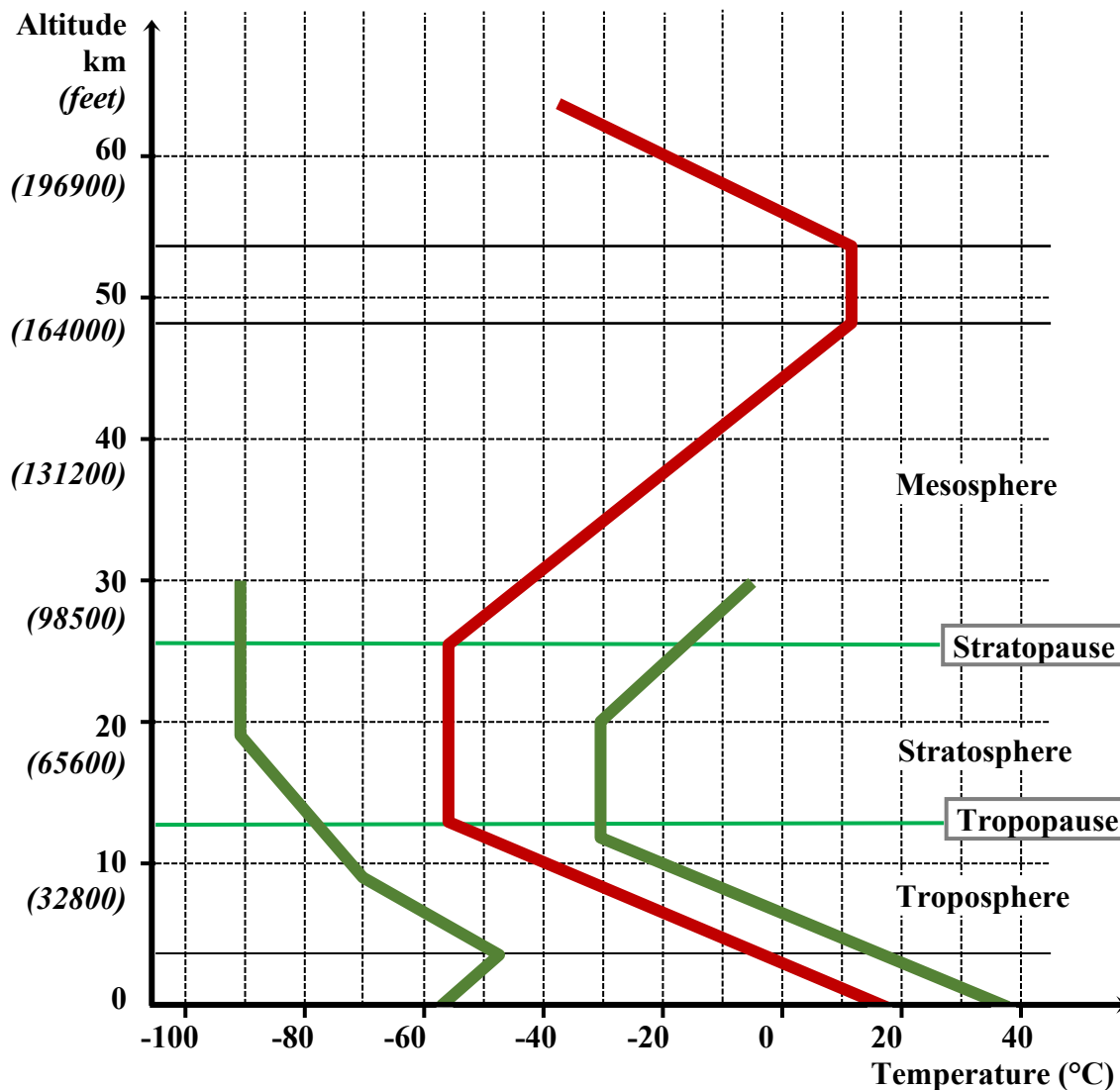


Figure 3 - Graph representing air temperature in relation to altitude

NOTE: Average temperature (central line) and extreme temperatures for a probability of 1 to 10 years, observed below latitude 45 °N between 0 feet and 200000 feet (0 m and 60000 m).

Table 2 - Composition of ambient air

Gas	Symbol	Fraction	Remarks
Nitrogen	N ₂	0.78101	Constant
Oxygen	O ₂	0.20946	Constant
Water	H ₂ O	$2 \cdot 10^{-2}$	Very variable
Argon	Ar	$9.17 \cdot 10^{-3}$	Constant
Carbon dioxide	CO ₂	$3.30 \cdot 10^{-4}$	Variable
Neon	Ne	$1.82 \cdot 10^{-5}$	Constant
Helium	He	$5.24 \cdot 10^{-5}$	Constant
Methane	CH ₄	$1.50 \cdot 10^{-6}$	Constant
Krypton	Kr	$1.14 \cdot 10^{-6}$	Constant
Ozone	O ₃	$5 \cdot 10^{-7}$	Very variable

- a. Gases in closed or semi-closed cavities. There are the gases contained in the digestive tract, the ear and sinus cavities, lungs, etc. They are believed to be the major cause of the pathological signs of barotrauma through the physical relationship defined by Boyle-Mariotte's Law (Pressure x Volume = Constant).
- b. Gases dissolved in body fluids. These are the gases dissolved in the blood, plasma, and other body fluids. The amount of gas dissolved in a fluid obeys Henry's Law which states that the quantity of gas dissolved in a liquid is proportional to the partial pressure of the gas in contact with the liquid. Movement of these gases out of body fluids are considered to result in the symptoms associated with the aviator's version of decompression sickness.¹
- c. Gases in chemical combination. The primary gases in respiration are oxygen and carbon dioxide. Blood transports a greater quantity of these gases than can be explained by simple adherence to Henry's Law. The explanation is the interactions of the gases with the red blood cells. Oxygen is chemically bound to hemoglobin. In normal conditions, 100 cm³ of arterial blood contains 0.23 cm³ (at 37 °C) of dissolved oxygen (by Henry's Law), and about 20 cm³ of chemically combined oxygen. Carbon dioxide is a metabolic waste product which must be eliminated from the body. Carbon dioxide content is based on a complex set of equilibria, which involve dissolution of CO₂ molecules, followed by a subsequent combination with water. The result is a change in pH.

5. CARDIOVASCULAR AND RESPIRATORY ANATOMY AND PHYSIOLOGY

5.1 Blood Circulation

Blood is circulated through the body by the heart and vessels. The total volume of blood contained in these organs is approximately 4.5 dm³ in normal adults.

5.1.1 Anatomy

The heart is a muscular pump divided into four chambers: left atrium, right atrium, left ventricle, and right ventricle. The right and left atria receive blood returning from the body and lungs, respectively, and work to assist in delivering the blood to the ventricles. The right ventricle pumps blood into and through the lungs (the pulmonary circulation). The left ventricle pumps blood into and through all other tissues (the systemic circulation). Separating atria and ventricles are muscular structures referred to as the interatrial and interventricular walls, respectively. The right heart and left heart are synchronized in rhythm, physiologically pumping an equal volume of blood through the pulmonary and systemic circulations. Blood circulations are organized in the following way (see Figure 4).

¹ Decompression sickness is a multifaceted condition brought about by a rapid change in atmospheric pressure. It is discussed in detail in Section 9.

Pressure resulting from the contraction of the left ventricle forces blood into an artery called the aorta. In the circulation, arteries carry oxygenated blood traveling away from the heart toward sites of cellular exchanges. Blood transporting the maximum amount of oxygen physically possible is said to be 100% saturated.² The aorta is the largest artery in the body and quickly gives rise to branches that ultimately supply blood to the entire body. The coronary arteries supply blood to the cardiac muscle and the carotid arteries supply the head. At the arch of aorta, the ascending aorta turns into the descending aorta, carrying blood to the trunk and lower limbs. As the large arteries travel throughout the body, they branch, giving rise to numerous small diameter vessels. The last small branches of the arterial system are referred to as arterioles. The role of the arteriole is to control the volume of blood flow into the capillaries. Capillaries are the smallest blood vessels in the body and are the site where gas exchanges between blood and cells take place.

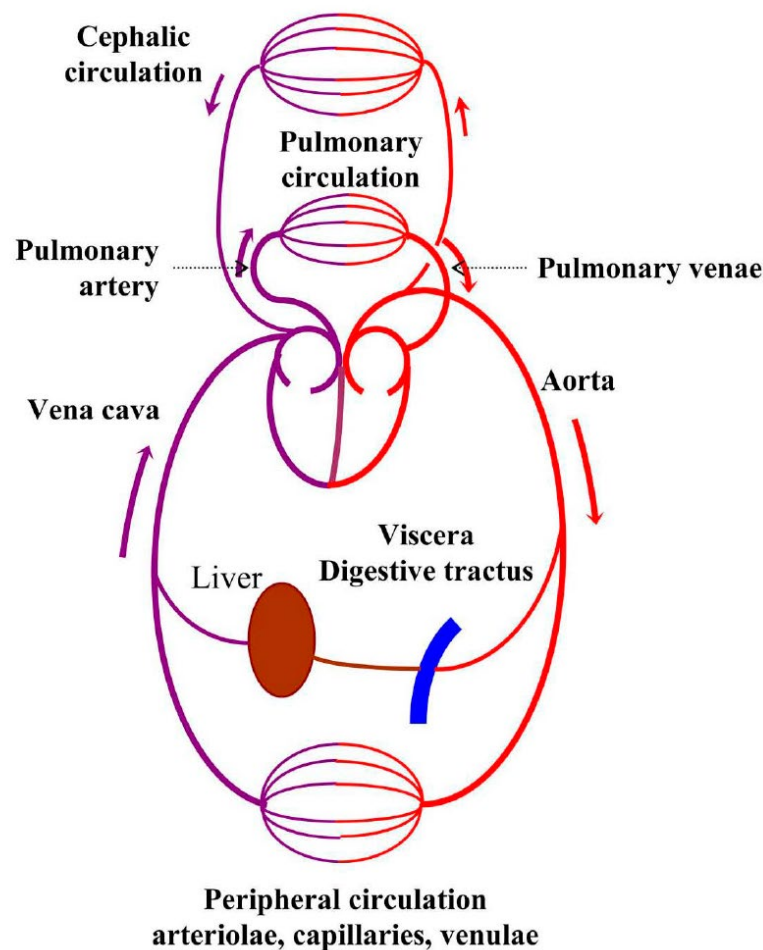


Figure 4 - General layout of the circulatory system

After exiting the capillaries, blood is collected by a network of blood vessels known as venules, which join together to form the veins that carry the oxygen depleted blood back to the heart and lungs. The two major veins in the body are the inferior vena cava which collects blood from the lower part of the body and the superior vena cava which collects blood from the head and upper limbs. The two venae cavae return blood to the right atrium. From the right atrium, the blood enters the right ventricle which pumps it through the pulmonary circulation. Anatomically similar to the peripheral circulation, the blood vessels branch repeatedly to ultimately form capillaries which then combine into veinules and veins on the return journey to the left atrium. From the left atrium, blood passes to the left ventricle for distribution through the body.

² Blood oxygen saturation (SaO_2) is often used as an index of hypoxia.

However, a major difference between the pulmonary and systemic circulation should be noted. The oxygenation state of the blood in the arteries or veins of the pulmonary circuit is reversed relative to the state in systemic circulation. The primary role of the pulmonary circulation is to provide for gas exchanges. Therefore, the pulmonary arteries carry deoxygenated blood away from the heart to the areas of gas exchanges within the lung (i.e., that returning to the right heart from the body), whereas the pulmonary veins carry oxygenated blood returning from areas of gas exchanges in the lung (i.e., that returning to the left heart from the areas of gas exchanges in the lung). Therefore, the oxygenation state of the blood being carried in pulmonary arteries and veins is opposite that of the systemic circulation.

5.1.2 Physiology

The basic function of the cardiovascular system is to provide a mechanism by which oxygen and nutrients can be delivered to the cells, and the waste can be eliminated from the cells. The cardiovascular system performs this role by the heart muscle contracting and creating pressure which forces the blood through the vascular system. The total blood volume is approximately 4.5 dm³. Normal functioning of an individual depends upon this blood delivering an adequate supply of oxygen to the tissues, particularly the brain.

The rhythmic contraction of the cardiac muscle provides the pressure which constantly forces the blood through the vascular system. The relatively brief period of contraction, systole, is followed by a period of relaxation, diastole. Systolic and diastolic blood pressure readings reflect the pressure within the cardiovascular system during these periods of contraction and relaxation. The atria contract prior to the ventricles and work to complete ventricular filling. Valves which direct the blood and prevent backflow separate the atria from the ventricles and both sides of the heart, and also separate each ventricle from its corresponding artery. In discussing the anatomy of the heart, the cardiovascular system was divided into pulmonary and systemic circuits. Functionally, differences in the arterial and venous segments of the two circuits must be considered.

At rest, the amount of blood pumped by the heart, the cardiac output, is approximately 5 dm³/min⁻¹. Cardiac output increases in response to increased demand for oxygen. For example, during a bout of maximum physical exercise, cardiac output can increase to 30 dm³/min⁻¹. Contributing to this increase in output is an increase in heart rate from resting levels of 60 beats/min⁻¹, to rates approaching, and sometimes exceeding, 200 beats/min⁻¹. Other changes occurring under demanding conditions include more intense contraction of the heart muscle and the muscular walls of the vasculature.

In terms of the vasculature, the arteries make up a high-pressure system. Pressure in the aorta averages 100 mm Hg. Pressure drops as blood flows through the systemic circulation falling to approximately 0 mm Hg by the time it returns to the right atrium. The venous side is a low-pressure system. The veins are very distensible and contain approximately 65% of the total blood volume. Under certain conditions, such as the exertion of increased G-force, the veins can actually distend and act as a reservoir for blood thus limiting the volume of blood returning to the heart. Obviously, the cardiovascular system must be able to adapt to such situational changes if normal functioning is to be maintained.

5.2 Ventilation

The tissue of the lung provides the interface for gas exchanges to take place. Ventilation is the process of moving volumes of gases in and of the lung.

5.2.1 Anatomy

The ventilatory system is made up of a network of branching tubes, an area dedicated to gas exchanges (see Figure 5), and a mechanical system to move air in and out of the lung. The transport tubes, i.e., bronchi, arise from the trachea and divide repeatedly as they descend into the lungs. The bronchial tree ends in what is referred to as the terminal bronchioles. Since no gas exchanges take place in these conducting bronchioles, they make up what is known as the anatomical dead space. The primary region of gas exchanges is the alveolar ducts which are completely lined with alveoli, the microscopic gas sacs of the lung. This alveolated area of the lung is known as the respiratory zone. The walls of the alveoli are heavily vascularized by the pulmonary capillaries. Gas exchanges take place across the extremely thin (1 µm, 10⁻⁶ m) alveolocapillary membrane, which represents a surface area of approximately 60 to 90 m².

Air is drawn into and forced out of the lung by pressure changes induced by changes in volume of the lung. Inspiration is an active event during which contraction of the diaphragm and intercostal muscles increases lung volume. The pressure becomes slightly negative with respect to the environment and air is drawn into the lung. Expiration is normally passive, the ventilatory musculature relaxes, the volume of the chest decreases, and the resulting increase in pressure forces air out of the lung. Typically, the movement of air results from pressure changes under 4 hPa (3 mm Hg) total.