Effects of aerospace environments on the cardiovascular system

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ABSTRACT

Certain physical and physiological changes occur in the atmospheric levels where flight and space activities take place. Air pressure decreases with increasing altitude and the partial pressure of O_2 decreases in parallel with the atmospheric pressure drop and creates hypoxia in the flight crew and in the passengers. In case of acute hypobaric hypoxia, blood is redistributed to the brain and the heart, whereas blood supply to internal organs, such as kidney and skin is reduced. Peripheral cyanosis can be observed on the fingertips and the lips during hypoxia-induced blood redistribution. Tachycardia develops, but the stroke volume does not change. The coronary blood flow increases in parallel with the rise of cardiac output; however, the presence of severe hypoxia leads to myocardial depression. Coronary reflex vasoconstriction is followed by cardiac arrest. Another important pathology caused by low pressure is decompression sickness. In this disease, immediate reduction of the environmental pressure leads to the dissolved nitrogen transforms into gas, and nitrogen bubbles form in the tissue and in the blood. These bubbles interfere the perfusion of the blood and cause ischemia. Symptoms and signs of cardiac decompression sicknesses are dyspnea, tachypnea, chest pain, cough, hemoptysis, cyanosis, retrosternal discomfort, and rarely, shock. Air embolism of coronary vessels manifests as rhythm disturbances, myocardial infarction, and circulatory collapse. The physical forces that occur because of aircraft movement and affect both the pilot and the aircraft, are called acceleration (G) forces. The basic physical effect of G forces is weight increments and motion restriction. During high +Gz, blood pressure decreases in the brain and increases in the lower extremities. Blood forced to move into the lower parts of the body and lower extremities. Thus, brain perfusion cannot be achieved, and loss of consciousness occurs at approximately +4 Gz acceleration levels. Earth also applies an acceleration force to the objects on or around the world. Therefore, gravitational force is also applied to orbiting spacecraft by Earth. The centrifugal force and the gravitational force are in an equilibrium, weightlessness is created inside the orbiting spacecraft, and this is called microgravity. Blood redistributed to the neck and head veins, and astronauts feel nasal fullness, and bulging around the eyes during space missions. As the time spent in the space progresses, a 22% decrease in plasma volume is observed in the cardiovascular system within 1 week owing to increased venous return, and this causes a temporary hemoconcentration. After staying one week in space, cardiac output increases by 22% whereas peripheral resistance decreases by 14%. Rhythm disturbances are also seen during activities performed in space is and thought to be caused by electrolyte imbalance or stress. There is an increasing demand for high altitude and space travel nowadays. These trips cause several physical and physiological effects on both passenger and flight crew. Therefore, it is necessary to take precautionary measures to carry out these activities safely.

Keywords: cardiovascular system, space, altitude, hypoxia, microgravity, acceleration forces

Introduction

Mankind has always dreamed of flying, and this dream eventually succeeded with balloon flights in the 19th century, enabling him to leave the environment he had adapted to live in. Certain physical changes occur in the atmospheric levels where flight activities take place, which could lead to some physiological changes in humans. In this article, we discuss the effects of aviation and space activities on the cardiovascular system (CVS), briefly elaborating on the basic physical and physiological effects of aerospace environment.

Aviation and space activities are executed in the upper levels of the atmosphere and in space. Oxygen (O_2) content of the atmosphere is 21%, and this ratio is quite constant with altitude gain, whereas air pressure decreases with increasing altitude. In accordance with Boyle's and Dalton's laws, the partial pressure of O_2 decreases in parallel with the atmospheric pressure drop and creates hypoxia in the flight crew and in the passen-

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gers if no measures are taken at high altitudes. The first system affected is the neurological system, resulting in disruption of cortical functions in pilots. Unless corrective action is taken, ultimately loss of consciousness will occur. The adaptation mechanism of our body against hypoxia is hyperventilation (1).

Another important pathology caused by low pressure is decompression sickness (DCS). In this disease, the nitrogen dissolved in the blood and tissues becomes supersaturated after decline in the environmental pressure according to Henry's law. Further or immediate reduction of the environmental pressure leads to the dissolved nitrogen not being removed sufficiently from the blood and tissues. Eventually, the dissolved nitrogen transforms into gas, and nitrogen bubbles form in the tissue and in the blood. The mechanisms mentioned above are the outcomes that appear in humans during acute exposure to a hypobaric environment. The adaptations that develop after prolonged exposure to high altitude are called acclimatization. High-altitude diseases such as acute mountain disease and acute brain and lung edema are observed in the lack of acclimatization (1).

The physical forces that occur because of aircraft movement and affect both the pilot and the aircraft, especially seen in military aviation operations or in acrobatic flight activities, are called acceleration (G) forces. G forces (vector) are named according to the affected axis. The G forces acting on the body in the anteroposterior or reverse directions are called transverse Gs, whereas those acting in right to left or left to right directions are called lateral Gs. G forces acting parallel to the body's long axis (head-to-foot or reverse direction) are called vertical Gs or "Gz." The basic physical effect of G forces is felt as weight increments and motion restriction. For example, a pilot who is exposed to an acrobatic movement of 9G increases weight by 9 times, that is, 80 kg of body weight increases to 720 kg under 9G exposure. A pilot under this force cannot leave the chair, raise his head, or move his arm easily (2).

According to the law of the gravity [$F = G (m^1 \times m^2)/r^2$], Earth applies an acceleration force of 9.8 m/sn^2 to objects on or around the world, and weight is produced by this force. According to this law, the distance between the object and the center of the Earth are indirectly proportional with the magnitude of the gravitational force. Therefore, gravitational force is also applied to orbiting spacecraft by Earth. Activities performed in the outer layers of the atmosphere and in space can only be possible with rotating spacecraft in the orbit. Spacecraft or space stations should rotate with a velocity of 27,000 km/h in this orbit so as to not fall onto the Earth. In this case, the centrifugal force and the gravitational force that counteract the spacecraft are in an equilibrium, and weightlessness is created inside this vehicle. This is called microgravity and is the reason why astronauts experience weightlessness in the spacecraft during space missions (3).

The basic physics and summary of aerospace medicine is mentioned above, and further reading can be done in the references of this article. Effects of aerospace activities on CVS is detailed below.

Effects of hypobaric environment on the cardiovascular system

The presence of acute hypobaric hypoxia caused by high altitude leads to a decline in partial pressure of O_2, rise of carbon dioxide (CO_2) pressures, and decrease of pH in the tissues, resulting in metabolic acidosis and hypoxemia in the tissues. Peripheral and central chemoreceptors that are sensitive to O_2, pH, or CO_2 responds to this developing hypoxemia and acidosis. The respiratory system's primary response against hypoxia is hyperventilation, leading to respiratory alkalosis (1, 4).

In case of exposure to acute hypobaric hypoxic environment, blood in the circulatory system is redistributed and directed to the brain and the heart, whereas blood supply to internal organs, such as kidney and skin is reduced. Tachycardia develops, but the stroke volume does not change. Because of the low partial pressure of O_2 at the altitude of 20,000 feet, 20%–25% increase in the heart rate is observed, and the heart rate doubles at an altitude of 25,000 feet. The coronary blood flow increases in parallel with the rise of cardiac output; however, the presence of severe hypoxia leads to myocardial depression. Coronary reflex vasoconstriction is followed by cardiac arrest. Cerebral perfusion is achieved by the balance between the vasodilatation effect of hypoxemia and the vasoconstriction effect of hypocapnia. When arterial O_2 pressure is at 35–40 mm Hg levels, brain blood supply increases by 50%–100%; however, during hyperventilation-induced hypocapnia, (arterial CO_2 pressure of 20 mm Hg), brain perfusion is reduced by 50%. With the effect of these two mechanisms, during breathing air, brain blood supply decreases up to altitudes of 15,000 feet, whereas cerebral perfusion increases between altitudes of 16,000 and 18,000 feet. Peripheral cyanosis can be observed on the fingertips and the lips during hypoxia-induced blood redistribution. A pilot experiencing acute hypoxia should descend to lower altitudes and must don the O_2 mask if available (5).

DCS is the most dangerous clinical pathology caused by unprotected presence in an acute hypobaric environment. The bubbles (the mechanism of formation of which has been described above) exert their effects via two main mechanisms. In the first mechanism, the bubbles occlude the lumen of the vein mechanically, disrupt perfusion, and press on the surrounding tissues. Ischemic symptoms occur in the tissues whose perfusion is impaired. The second mechanism is that the bubbles in the vein create a surface effect that trigger thromboembolic processes. In DCS, the bubbles in circulation act as air emboli first; and if not intervened properly, pose a risk of thromboembolism. The bubbles are mostly formed in the lower extremity venous system and are removed from the circulation by pulmonary filtration. These bubbles are called silent bubbles or venous gas embolism. In the presence of congenital, physiological, or acquired right to left shunts, the bubbles may pass to the arterial circulation and form the arterial gas embolism. The bubbles that appear in DCS generate signs and symptoms according to the system in which they are located. Because the signs and symptoms are similar in cardiac and pulmonary decompression sicknesses, these are often difficult to distinguish. Symptoms and signs of cardiac and pulmonary decompression sicknesses are dyspnea, tachypnea, chest pain, cough, hemoptysis, cyanosis, retrosternal discomfort, and rarely, shock. Air embolism of coronary vessels manifests as rhythm disturbances, myocardial infarction, and circulatory collapse. DCS requires urgent intervention with the use of hyperbaric O_2 therapy. If it is encountered during a flight, O_2 mask must be donned without delay, and immediate descent to a lower altitude and landing at the nearest airport should be planned. An aerospace medicine specialist or undersea hyperbaric medicine specialist should be contacted as soon as possible (6).

Effects of G forces on the cardiovascular system

The hydrostatic pressure created by the blood column in the blood vessels of a standing person is calculated by the formula, P=pGz. In this formula, "p" is the blood fluid density, "G" is the gravitational force applied by the Earth, "z" is the vertical height of the blood column; and when the constant values are calculated, the formula transforms into "P=0.78z." Vertical distance between the heart and the vertex is considered to be 38 cm. When this formula is calculated with these parameters, during each +1 Gz increase, the blood pressure drops by 30 mm Hg at the vertex level. During high +Gz, blood pressure decreases in the brain and increases in the lower extremities. Thus, redistribution occurs, and blood moves to the lower parts of the body and lower extremities during high +Gz exposure. Normal systolic blood pressure value is around 110–120 mm Hg at the heart level, thus brain perfusion cannot be achieved, and loss of consciousness occurs [G induced loss of consciousness (G-LOC)] at approximately +4 Gz acceleration levels. Because of an intraocular pressure of 10–20 mm Hg, retinal perfusion is disrupted 0.5–1 G lower than the brain levels; and the ocular symptoms like blackouts, gray out, and tunnel vision are seen before G-LOC. Therefore, the pilots who experience visual symptoms during maneuvering knows that these signs are pre or alerting signs of G-LOC (2).

Control of blood pressure is regulated by the thoracic and carotid baroreceptor reflexes and introducing their effects by the autonomic nervous system. When a decline in blood pressure is detected, a pressure-boosting response occurs via the activation of the sympathetic nervous system and leads to an increase in blood pressure, heart rate, stroke volume, and total peripheral resistance. Although the baroreceptor reflex is very effective in compensating for the drop in blood pressure, this effect takes 6–12 seconds. Heart rate increases to 120–140 beats/min under +4Gz, and venous return increases in 10–15 seconds. In addition to the baroreceptor response, the sympathetic nervous system also activates the endocrine system, which causes an increase of epinephrine, norepinephrine, and cortisol levels in blood. The endocrine system response is much slower than the baroreceptor reflex, but it is important in case of prolonged or repeated exposure to G forces (2, 7).

Effects of microgravity and space operations on the cardiovascular system

Although working in a weightlessness environment seems attractive and fun, exposure to microgravity causes many negative physiological effects. Space operations consist of 4 main phases; launch, reaching the orbit, orbit period, and return to Earth. Astronauts wait in a supine position with their legs in the upward flexion position for 2.5–4 hours before the launch and during take-off. During this phase, cardiac preload increases, and stroke volume increases from 75 mL/beat to 90 mL/beat. Blood is redistributed to the head and upper parts of the body with the effect of posture and microgravity in the launch and orbit periods. Astronauts feel redistribution of blood as a prominence of the neck and head veins, nasal fullness, and bulging around the eyes. As the time spent in the space progresses, a 22% decrease in plasma volume is observed in the CVS within 1 week owing to increased venous return, and this causes a temporary hemoconcentration.

Microgravity can be simulated with parabolic flights on Earth. It was reported that cardiac output increased by 29%, peripheral vascular resistance decreased by 24%, and mean blood pressure did not change during 20 seconds of weightlessness simulated in parabolic flights. After staying one week in space, cardiac output increases by 22% whereas peripheral resistance decreases by 14%. The heart volume increases to overcome the increased preload on the first day of the space flight, but total heart volume starts to decrease from the second day because of the decreased plasma volume until the seventh day and remains fairly stable after one week. This final volume of the heart is smaller than its pre-launch volume.

Another pathology of CVS seen during activities performed in space is rhythm disturbances. These rhythm disturbances were recorded during activities in which astronauts were monitored, such as exercising, applying negative pressure to lower parts of the body, and space walks. They are thought to be caused by electrolyte imbalance or stress. It has been reported that 31 ECG findings and 75 rhythm disturbances were detected in the "Mir" operations carried out by Russia in the 10-year period (8, 9).

Astronauts are subjected to a very low +Gz between 1.3 and 1.5 lasting for 20 minutes during the return period of the space operations. Even these very low +Gz can introduce very high +Gz (+6 Gz) equivalent CVS effects in the microgravity adapted astronauts after 16 days of space travel. These very low acceleration forces may cause loss of consciousness in returning astronauts. After returning to Earth, the most important pathology that occurs in the CVS is orthostatic hypotension with 27% of the returning astronauts experiencing presyncope/syncope during the 10-minute stand-up test after short-term space travel, and they are placed in a sitting position. It has been reported that orthostatic hypotension is caused by decreased brain perfusion or decreased mean arterial pressure in some individuals. In short-term space flights, maximum exercise capacity in space is preserved; however, after returning to Earth, maximum exercise capacity decreases by 16% in fit and by 6% in unfit individuals. It is reported that exercise in space is the best proven method to reduce return adaptation difficulties, such as orthostatic hypotension (8, 9).

Conclusion

There is an increasing demand for high altitude and space travel today. These trips cause several physical and physiological effects on both passenger and flight crew. Therefore, it is necessary to take precautionary measures to carry out these activities safely.

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