1 The aircraft cabin

1.1 Cabin pressurization

There are many fundamental differences between air travel and ground transportation. Today's modern jets fly at altitudes between 30,000 and 40,000 feet. The Concorde, which is no longer in service, attained an altitude of 48,000 feet. The jet engines currently in use function effectively in thin air, and therefore at higher altitudes. Future developments are expected to not only meet, but to exceed these altitudes. Suborbital flights will subject crew and passengers to entirely new demands.

The atmospheric conditions found at flight altitudes places humans into an environment that is not survivable without appropriate technological measures. The temperature is around –60° Celsius, and the atmosphere is extremely thin and therefore does not contain enough oxygen for respiration. The consequence would therefore be death by freezing and hypoxia. The remedy is provided by cabin pressurization, which began in commercial aviation in the 1950s with piston engine airplanes, and which subsequently became the technical standard in jet engine aircraft. Information regarding the function of the pressurization and air conditioning systems in modern commercial aircraft is therefore presented here. On the one hand, these physical and physiological conditions set the prerequisites for the determination of the aeromedical fitness of passengers, and on the other hand, they set the limitations for care and emergency treatment on board, as well as for the feasibility of transporting ill passengers in commercial aircraft.

Modern airliners are powered by jet engines, where 80% of the thrust comes from the so-called bypass system and 20% through the engine exhaust. This makes for more economic utilization of fuel and also is more efficient, quieter, and produces less pollution. In principle the air is drawn in and compressed, causing it to heat up. This occurs over several stages, and eventually kerosene is injected and ignited. The exhaust contributes only a small portion of the generated thrust. The majority is created by the fan and secondarily by the turbines, which generate and deliver the greater portion of the propulsion in the bypass system. No combustion occurs here, and the cold bypass stream that is generated helps dampen engine noise.

The second of three compression stage of the turbine, in other words, before fuel injection occurs, is where the so-called "bleed air" is tapped and fed to the cabin pressure/air conditioning system. Compression heats the air to about 220° C. This is where the first problem arises, which is the low relative *humidity* in the cabin. Air at flight altitude is quite dry – only about 3% relative humidity, and this is reduced even further by the effects of compression. After subsequent cooling, the cabin air becomes extremely dry. It is sent to the individual seat rows through a distribution system, and flows in a far-reaching laminar flow along the cabin walls. In wide-body jets with two aisles, it also flows down from the luggage compartment areas, is eventually collected at the floors and exhausted through a collection system. Depending on the number of passengers on board, a portion of this air is drained through an outflow valve at the rear, while another portion is cleaned through a highly effective filtration system and admixed with fresh air (bleed air). This so-called *recirculated air* brings cabin humidity up to 8–15%. As an example, a Boeing B747-400 with a cabin volume of 1,900 m^3 provides an air exchange of 16 to 24 times per hour, depending on the numbers of passengers.

The effective cabin *air pressure* is not, as is often quietly assumed, the same as at sea level. Due to technical reasons, such as enhanced structural requirements and thus greater weight, the cabin altitude is kept between 1,800 m and 2,450 m. Therefore the cabin pressure is lower than at sea level. The International Civil Aeronautical Organization (ICAO) allows a maximum cabin altitude of 3,000 m – a level that is not normally achieved in today's modern aircraft. It is only approached when the destination airport is at a higher altitude, such as La Paz in the South American Andes Mountains.

This choice of cabin altitude was not reached arbitrarily, but rather guided by physiological principles. The healthy human organism tolerates an altitude of up to 3,000 m (about 10,000 feet) quite well by adaptation, and therefore problems are not expected.

A relevant point is that the cabin pressure naturally does not remain constant, but changes according to flight level. After takeoff, it declines incrementally to a minimum, only to rise again through descent to landing. Pressure changes can also occur at cruise altitudes (see Fig. 1).

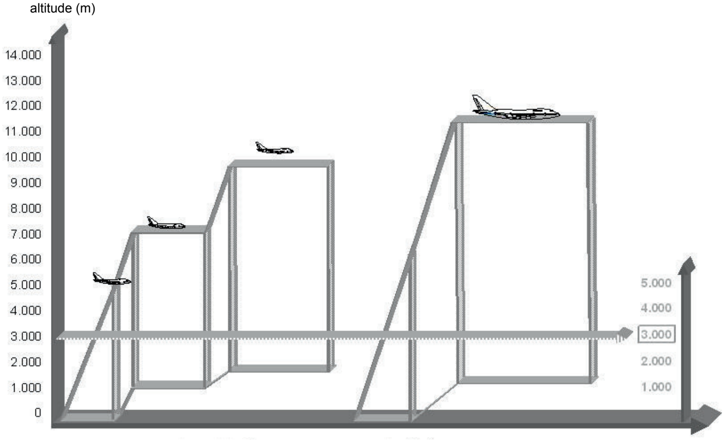

Fig. 1 Cabin pressure vs. outside pressure

In the past, cabin pressure was set manually by the flight engineer, while today it is automatically regulated in relation to the outside pressure. This technique is more comfortable for the passenger, as it allows for smoother transitions. Nonetheless, in certain situations dependent on air traffic control specifications and flight profile requirements, cabin pressure can be rapidly adjusted by hand. Theoretically it is possible to construct the cabin and air conditioning system in such a way as to maintain a pressure equal to that on the ground. However, this would lead to higher weights due to increased structural requirements, thereby reducing range and load capacities and resulting in higher ticket prices.

A brief mention regarding *temperature* should also be made. Cabin temperature is controlled independently for different sections of the aircraft. The Airbus A340, for example, has six zones in which individual temperatures can be set. Depending on passenger load, electromagnetically driven valves can mix compressed, re-cooled air from the so-called *pack* with diverted warm air. At this point it is worth mentioning a phenomenon that often causes concern and worry for laypeople thinking that there may be a fire on board. After landing in hot, tropical areas with high humidity, the cabin is cooled for comfort. By virtue of this cooling of moist outside air, which is brought in through the air conditioning system, thick plumes of vapour can be seen coming out of the overhead gaspers.

In keeping with the *"fail safe principle",* which means that for each system in the airplane there is at least one (often two, three or more) redundant system in the event of malfunction, there are two, or even three, air conditioning systems. Therefore even in the event of a rapid decompression, a sudden loss of pressurization is safeguarded against while an appropriate lower flight level can be attained to minimize health hazards.

1.1.1 The gas laws

There are three main gas laws that are important to mention when discussing environmental conditions in an aircraft cabin. They are listed below in order of significance for aviation medicine:

1. Boyle-Mariotte law
2. Dalton's law
3. Henry's law

The Boyle-Mariotte gas law

This law states that the volume of a gas (or a mixture of gases) at a constant temperature and humidity is inversely proportional to the pressure to which it is subjected. Gas pockets in the human body are usually composed of air with a high moisture content, so that the vapor pressure of 47 mmHg must be subtracted, resulting in this equation:

$$\frac{V_2}{V_1} = \frac{pG_1 - pH_2o}{pG_2 - pH_2o}$$

Air is a mixture of gases in which the pressure declines logarithmically, and at an altitude of about 5,000 m is reduced to half. As a rule this pressure change is not dangerous, but neither is it irrelevant as it can cause significant discomfort as well as pain. All passengers are affected similarly. Particular predisposing factors that are not manifested at sea level can lead to painful symptoms through pressure differences, such as eardrum anomalies or problems in the nasal sinuses.

Dalton's gas law and oxygen delivery

Air is a mixture of nitrogen, oxygen and minute amounts of a variety of noble gases. According to its percentage of the total, each gas exerts its proportional share of the total pressure according to the following equation:

$$p_{ges} = p_1 + p_2 + p_3 + p_4 + p_5 + \dots + p_n$$

Again, this assumes constant temperature and humidity. As before, normal travellers are subject to this effect, and it carries particular significance with regard to oxygenation. As the total pressure decreases, so does the partial pressure of oxygen with a corresponding reduction in *oxygen saturation of the blood*. This process, too, does not run linearly, but logarithmically. The human body has the ability to compensate to a certain degree (see Fig. 2), basically up to a pressure altitude of 3,000 m; above that, compensation is time-limited or not possible at all.

Furthermore, the laws of gas diffusion must be taken into consideration. This purely physical process is passive and always runs in the direction of falling pressure gradients until equilibrium in both compartments is reached. The medium in which this process takes place plays no role. Media can be gaseous, liquid or solid and do not necessarily have to be subdivided by membranes – although this is, of course, always the case in biology. The speed of diffusion depends not only on the concentration gradient, but also on the thickness and permeability of the membrane and the size of the molecules of the respective substance(s). Another factor is the diffusion surface area. Certain lung diseases create thickened alveolar membranes and reduced surface areas, resulting in a further reduction of arterial pO_2 and oxygen saturation (see Fig. 3).

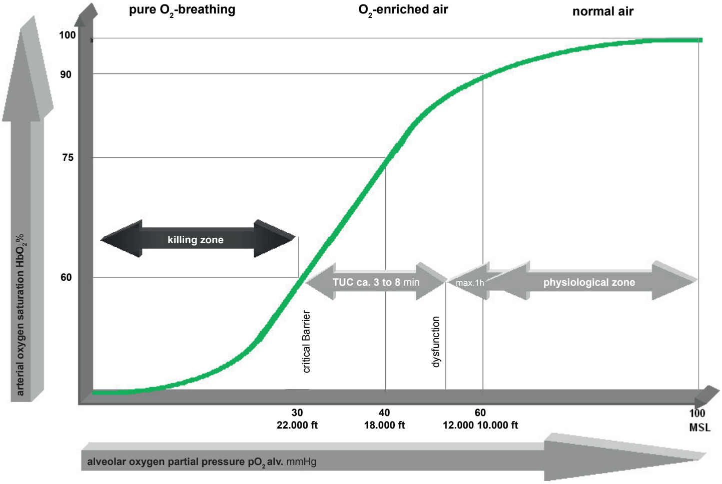

Fig. 2 Oxygen binding chart

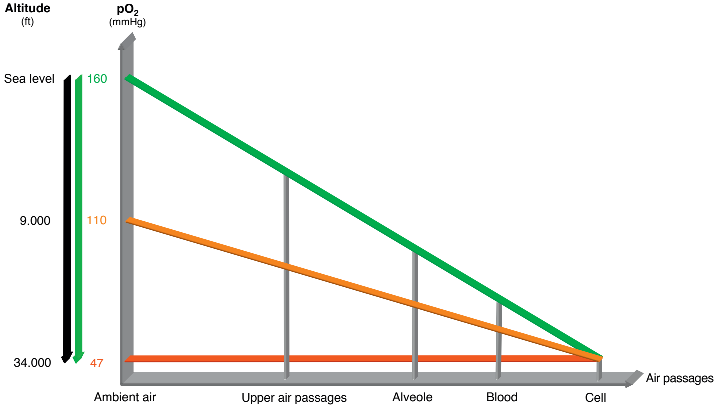

Fig. 3 Oxygen saturation chart: Oxygen pressure reductions in MSL (green) and at 2450 ft (orange); Ambient oxygen pressure in cruising altitude of 34.000 ft or above (red). MSL = Mean Sea Level

The effect of *Dalton's law* is very important with regard to aeromedical evaluation in that diseases of the cardiovascular system, the lungs, and the blood are significantly impacted. It describes the problems associated with hypoxia – of which there are four types. They all have the same outcomes, but arise from different causes.

Hypoxic hypoxia is caused by insufficient oxygenation in the inspired air, when the partial pressure is too low, as it occurs with increasing altitude. This does not normally happen in commercial aviation as the aircraft is always pressurized to a comfortable level. In the event of a decompression, oxygen masks drop from above the seats and the aircraft rapidly descends to a safe pressure altitude. Other complicating factors are diseases of the gas exchange system in the lungs, such as thickening of the alveolar membranes or a reduction in gas exchange surface areas often found in patients with emphysema.

Anaemic or *hypovolaemic hypoxia* is caused by an insufficient O_2 transport capacity of the blood. Primary anaemia or blood loss is first on the list. Toxic gases such as carbon monoxide or substances such as nitrates or sulphur compounds lead to similar effects due to their high affinity for haemoglobin.

Histotoxic hypoxia is the result of a disorder of oxygen utilization within the cell, such as cyanide poisoning. But also narcotics and alcohol significantly impair oxygen utilization.

Circulatory (stagnant) hypoxia is caused by a circulatory failure, which can arise from a variety of sources.

Henry's gas law

Gases dissolve in liquids and body tissues. The amount of gas dissolved in solution varies directly with the pressure of that gas over the solution or within the tissues. This gas law is described in the following equation:

$$\frac{p_1}{p_2} = \frac{Q_1}{Q_2}$$

The emphasis in this case is primarily on the tissues and only secondarily on fluids, therefore it should be pointed out that different tissue structures have different affinities to various gases – especially to nitrogen.

Henry's gas law plays a minor role in aviation medicine. It explains the mechanism of decompression illness of divers (Caisson's disease). Its effects are not seen often in daily practice.

1.2 Humidity

Due to the extremely low humidity of the air at flight levels processed by the pressurization system in commercial aircraft, cabin air is relatively dry. After an hour of flight, the humidity drops to a level between 8 and 15%. There is a linear relationship between the humidity and the number of passengers on board (see Fig. 4). In a fully occupied B747-400, a maximal humidity of 15% can be achieved. Even the proportion of recirculated air plays a significant role. The greater the amount of incoming fresh air, the lower the humidity. Humidity is generated exclusively from the recirculated air component, which is cleaned by HEPA filters and mixed into the air circulation. This has a direct influence on the level of comfort.

The mucous membranes of the mouth and nose dry out, generating a sensation of thirst which increases fluid intake. However, kidney function does not initiate a diuresis, but rather the fluids shift to the extravascular space of the lower extremities due to the relative immobility and mild hypoxia.

Simultaneously, the dry air affects the conjunctivae, resulting in nonspecific irritation and a foreign body sensation in the eyes. This is why it may be a good idea to instill artificial tears. Contact lens wearers should consider taking extra precautionary measures.

1.3 Temperature

In contrast to many air conditioning systems, the technical solution for temperature control is not a significant problem. Because the passenger compart-

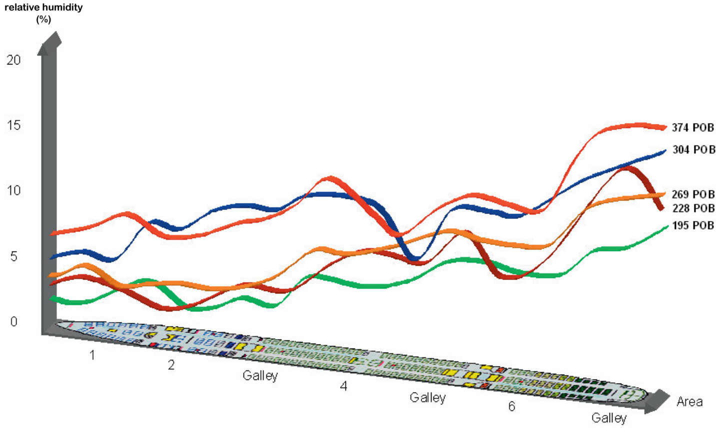

Fig. 4 Relative humidity, and distribution in the cabin (POB = Passengers On Board)

ment is divided into many (up to eight) zones, temperature regulation can usually meet the demand. Nonetheless, there are also some limitations. The sizes of the sections are dependent on construction requirements and cannot be altered. The class sections do not necessarily conform to these zones. It is therefore entirely possible that the temperature zone in the spacious business class may carry over to the more densely packed economy class. A dilemma may then arise: If the area that is less densely occupied is kept comfortable, it may become too warm for the other zones and vice versa.

With this in mind, it is recommended that one should wear warm clothes while flying – even when travelling to tropical countries. This is all the more important because many flights, especially to the Far East and Southern Africa, are night flights. Appropriate clothing promotes better quality of sleep when considering the lower body temperatures that are experienced during night and early morning hours.

Incidentally, the cargo hold is air conditioned as well.

1.4 Extraterrestrial radiation

In general, extraterrestrial radiation is not a problem for the normal passenger. A flight from Frankfurt to the west coast of the United States, such as to Los Angeles, results in an exposure of 30 µSv. A flight to Japan via a polar route results in 62 µSv and a flight to Rio de Janeiro in 18 µSv. The different doses are caused by the variability of the protective magnetosphere of the Earth. It is less in the polar regions than in the equatorial latitudes.

The European radiation regulatory agency UTA recommends a maximum of 20 mSv for travellers over a period of 5 years, and not more than 4 mSv annually.

Caution is recommended for first trimester pregnancies. There is no data regarding early fetal damage. In Germany, maternity protection law prohibits further flight duty for flight attendants and pilots during pregnancy.

1.5 Special exposures

A variety of other influences can negatively affect comfort during long flights, even though they may not be related to health issues. Some of these factors have been eliminated with technical solutions; others are prohibited by law.

First and foremost, *smoking on board* has been an issue in the past. Despite partitioning into the corresponding sections and elaborate air conditioning, the problem was never satisfactorily solved for the adjacent sections. Only since the regulatory agencies issued a general smoking ban for all flights the complaints have ceased.

A similar situation existed with regard to *ozone loads* until ozone catalytic converters were introduced. Particularly in the spring and on North Atlantic routes, ozone can project deeply into the atmosphere. By flying through these ozone layers, it can be brought into the cabin through the air conditioning system, which does not contain any measuring or warning devices. Typical complaints include: dry cough, retrosternal burning, pronounced irritation of the eyes, etc. The problem was solved in 1995 with the introduction of ozone catalytic converters which convert this gas into harmless O_2.

Periodically, the public is confronted with reports that the air conditioning system of airplanes *promotes the transmission of infectious diseases*, such as tuberculosis, to other passengers. For many reasons these reports are not accurate; in individual cases transmission does occur – but by other routes! By virtue of the technical construction of the air conditioning system, the air flow routing, the highly efficient filtration systems (HEPA) and the extremely dry air, transmission via this route is ruled out. However, it is quite possible that the previously ill person can disperse infection in his or her immediate vicinity by way of droplet contamination, or by moving through the aircraft such as to the lavatory or the galley. In reported cases, the recommendations of the World Health Organization (WHO) are followed and those passengers who were in the area where droplet spread could have occurred, namely two rows in front of, beside and behind the infected passenger, are notified. The HEPA filters are so effective that even particles the size of a virus are eliminated. A number of independent research institutes and organizations have repeatedly studied and verified this on several flights.

In new aircraft, as in newly constructed buildings, a variety of solvent residues may emanate from plastics, glues and carpets. These concentrations are well within the limits set by the regulations on *maximum allowable concentration (MAC)*, and generally only play a short-term role as they dissipate after a few flights due to the high air exchange rate, and only occasionally recur after repairs and maintenance.

Carbon dioxide accumulates in the area of the galley more than in other compartments of the cabin. The source is dry ice used for cooling the food and beverages. Here, the regulatory limits can definitely be reached, but are not exceeded. There is no concern regarding the passenger.

The aircraft is disinfected and disinsected by an exterminator at regular intervals during its lifetime in order to avoid a pest infestation.

1.6 Space and mobility

Flight times are getting longer, and some routine commercial flights are up to 18 hours in duration. With few exceptions, and according to seating class, the space limitations result in various types of discomfort – some of which could be considered as health issues. The relative immobility leads to tensions in the back muscles, and pain in the spinal column, pelvis and leg musculature. The large joints can become painful and stiff. This is due to *sitting in one position for a long time*. These complaints are transitory in nature. The lower legs can become swollen with secondary circulation disturbances. In persons who are particularly predisposed, *deep vein thrombosis* can develop, with the possibility of pulmonary embolism in individual cases.

Particularly at risk are individuals with varices and/or other risk factors such as obesity, nicotine use, genetic disposition, or use of oral contraceptives.

At this point, a brief mention of a **legal perspective** should be made. Periodically passengers attempt to make the airline liable for health problems that develop during flight to obtain compensation for injury or pain. There are several unequivocal rulings in German case law which have determined that travelling inherently carries a risk. This means that many things in daily life have an associated risk and that the individual must take this into account.