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Part II

MANUAL OF CIVIL AVIATION MEDICINE
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PART II. AVIATION PHYSIOLOGY

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INTERNATIONAL CIVIL AVIATION ORGANIZATION

Part II

Chapter 1. PHYSIOLOGICAL FACTORS OF RELEVANCE TO FLIGHT SAFETY

INTRODUCTION

General

Throughout the ages of evolution most higher mammals, including humans, have become biologically adjusted to an existence in the earth's atmosphere at or near sea level. Departure from this natural habitat by aerial flight can cause serious and possibly fatal disturbances unless either adequate physiological adjustments have time to take place or artificial means for life support are employed, depending upon the altitude involved and the duration of exposure.

This chapter is intended to familiarize the designated medical examiner with some of the basic principles of aviation physiology related to the working and environmental conditions encountered in civil aviation; a brief description will also be made of the man-machine relationship, the physical and mental demands imposed on aviation personnel, and the medico-biological aspects conducive to safe civil aviation operations. However, a single chapter does not do justice to this important topic, and the interested reader is therefore referred to one of the standard textbooks in aviation medicine for further information. Two examples of such texts are provided at the end of this chapter.

The human being is the most important element in the aviation system, and a healthy and competent crew is a prerequisite for safe and efficient flight. The philosophies underlying initial certification and continuing integrity of both the man and the machine are in fact analogous.

Advances in aviation research, development and improved technology have served to minimize the probability of human failure of the man-machine system. Being one of the vital elements in this system, man should be properly assessed from somatic and psychological viewpoints, taking into account the requirements for the task to be accomplished.

The rapid development of aviation during the past decades and the ever increasing number of individuals of all ages who avail themselves of air travel, have stimulated extensive research on the physiological effects of altitude in order to define tolerable and safe limits of exposure and to develop the most effective protective measures. In this respect, this chapter includes a short description of some technological necessities, e.g. cabin pressurization and oxygen systems, which permit life in otherwise hostile environments.

Human factors specified in Annexes

ICAO regulatory documents – Annexes – make many references to human factor aspects of civil aviation operations. Annex 1, 1.2.4.4.1 specifies that "Medical examiners shall have received training in aviation medicine and shall receive refresher training at regular intervals. Before designation, medical examiners shall demonstrate adequate competency in aviation medicine." In addition, 1.2.4.4.2 requires that "Medical examiners shall have practical knowledge and experience of the conditions in which the holders of licences and ratings carry out their duties", followed by a Note in which it is stated that "Examples of practical knowledge and experience are flight experience, simulator experience, on-site observation or any other hands-on experience deemed by the Licensing Authority to meet this requirement."

Part I, Chapter 1 of this manual also describes the relevant provisions contained in Annex 6 concerning oxygen in flight and fitness of flight crew members, as well as limitations of flight time intended to ensure that fatigue does not endanger the safety of a flight.

Annex 6, Part I, 6.12 describes the relevant provisions concerning radiation indicators to be carried by aeroplanes intended to be operated above 15 000 m (49 000 ft).

Figure 1.— Flight deck of an Airbus 330 (courtesy – Airbus)

Working environment

The designated medical examiner must be familiar with the design and operation of aircraft cockpits and air traffic control towers, so as to enable an adequate assessment of licence holders. Aircraft cockpits are designed in such a way that the flight crew member can function optimally not only under normal but also under critical conditions such as peak workloads. The main factors to consider in this working environment are graphically depicted in Figure 1. The major portion of information gathering is by vision; therefore limitations of human vision with respect to both acuity, the size and shape of the peripheral visual fields, and colour perception must be considered against the problems of access to visual information presented from both inside and outside the cockpit.

The position and operation of controls and flight instruments are fundamental. All controls should be within easy reach of the crew and all instruments should be easy to read. This will permit the pilot to acquire the information without interference (sensory acquisition) and permit him to operate all the controls efficiently (effector function).

The air traffic controller’s workload is subject to wide variation. It depends on such factors as the number of aircraft supervised, the complexity of air traffic routes, individual aircraft speed and relative aircraft movement comprising fast and slow aircraft, arrivals, departures and en-route traffic.

An example of the working environment of air traffic controllers is shown in Figure 2. It should be noted that good manual dexterity and neuromuscular co-ordination are required of controllers in the discharge of their duties. Good visual acuity, both at distance and for reading is required, and the amount of colour coded information makes good colour perception necessary. Furthermore, air traffic controllers should be capable of spreading their attention over a number of tasks simultaneously.

Figure 2.— Air Traffic Controllers at their work stations

PHYSICS OF THE ATMOSPHERE

Barometric pressure

The earth is surrounded by a thin layer of gases and vapours in which two forces counteract: the kinetic energy of the gas molecules leading them away from each other, and the gravitational attraction due to the mass of the earth. This attraction is inversely proportional to the square of the distance. The action of these two forces results in a decrease, with increasing altitude, in the density of the atmosphere and therefore a decrease in the resulting barometric pressure which follows an exponential curve with increasing altitude. Associated with this pressure event are other phenomena such as a temperature drop and an increase in the intensity of solar radiation. From a biological viewpoint, the barometric pressure drop is the most specific feature of the altitude climate. The manifestations directly related to reduced barometric pressure *per se* are of two types:

a) mechanical (expansion of trapped gases); and

b) biological (drop in oxygen partial pressure).

The chemical composition of the atmosphere remains constant up to an altitude of about 25 km (82 000 ft). The oxygen fraction is about 20.94 per cent and the partial pressure (pO_2) changes in direct proportion to the total barometric pressure (PB) and can be calculated for dry gas as follows:

$$P_{O_2} = P_B \times 0.2094 \qquad (1)$$

On entering the airways, the inspired gas becomes immediately saturated with water vapour at body temperature. The partial pressure exerted by the water vapour at 37°C (98.6°F) is always 47 mm Hg regardless of the total barometric pressure. This fact poses a special problem in aviation medicine because it is obvious that with increasing altitude, the water vapour pressure represents an increasing proportion of the inhaled gaseous constituents of the atmosphere. When considering the water vapour pressure, formula (1) has to be modified as follows:

$$P_{O_2} = (P_B - 47) \times 0.2094 \qquad (2)$$

Since aviation operations are carried out in an environment different from the regular habitat of humans, the designated medical examiner should be familiar with the physical characteristics of the environment in which the flight crew operates.

Table 1 shows the relationship between altitude, pressure and temperature as shown in a standard atmosphere.

ALTITUDE		PRESSURE		TEMPERATURE	
metres	**feet**	**mm HG**	**psia**	**°C**	**°F**
sea level		760	14.7	15.0	59.0
400	1 312	725	14.0	12.4	54.4
600	1 968	707	13.7	11.1	52.0
800	2 625	691	13.4	9.8	49.6
1 000	3 281	674	13.0	8.5	47.3
1 500	4 921	634	12.3	5.3	41.5
2 000	6 562	596	11.5	2.0	35.5
2 500	8 202	560	10.8	–1.2	29.7
3 000	9 842	526	10.2	–4.5	23.9
3 500	11 483	493	9.5	–7.7	18.1
4 000	13 123	462	8.9	–11.0	12.2
4 500	14 764	433	8.4	–14.2	6.4
5 000	16 404	405	7.8	–17.5	0.5
5 500	18 044	379	7.3	–20.7	–5.3
6 000	19 685	354	6.8	–24.0	–11.2
6 500	21 325	331	6.4	–27.2	–16.9
7 000	22 966	308	6.0	–30.5	–22.9
7 500	24 606	287	5.6	–33.7	–28.6
8 000	26 246	267	5.2	–36.9	–34.5
10 000	32 808	199	3.8	–49.9	–57.8
12 000	39 370	146	2.8	–56.5	–69.7
14 000	45 931	106	2.0	–56.5	–69.7
16 000	52 493	78	1.5	–56.5	–69.7
18 000	59 054	57	1.1	–56.5	–69.7
20 000	65 616	41	0.80	–56.5	–69.7
25 000	82 020	19	0.37	–51.6	–60.9
30 000	98 424	9	0.17	–46.6	–51.9

Table 1.— The relationship between altitude (in ft),
pressure (in mm Hg and pounds per square inch (absolute)), and temperature (in °C and °F)

The range of environmental conditions encountered in civil aviation operations varies widely, from those characteristic of unpressurized small aircraft and gliders, to those of subsonic and supersonic jets.

The relationship between barometric pressure and the operational ceiling of aircraft is shown in Figure 3, demonstrating the decrease in barometric pressure with increasing altitude.

Physiological effects of hypoxia at different altitudes are given in Table 2.

1) 2 450 m (8 000 ft): The atmosphere provides a blood oxygen saturation of approximately 93 per cent in the resting individual who does not suffer from cardiovascular or pulmonary disease.

2) 3 050 m (10 000 ft): The atmosphere provides a blood oxygen saturation of approximately 89 per cent. After a period of time at this level, the more complex cerebral functions such as making mathematical computations begin to suffer. Flight crew members must use oxygen when the cabin pressure altitudes exceed this level.

3) 3 650 m (12 000 ft): The blood oxygen saturation falls to approximately 87 per cent and in addition to some arithmetical computation difficulties, short-term memory begins to be impaired and errors of omission increase with extended exposure.

4) 4 250 m (14 000 ft): The blood oxygen saturation is approximately 83 per cent and all persons are impaired to a greater or lesser extent with respect to mental function including intellectual and emotional changes.

5) 4 550 m (15 000 ft): This altitude gives a blood oxygen saturation of approximately 80 per cent and all persons are impaired, some seriously.

6) 6 100 m (20 000 ft): The blood oxygen saturation is 65 per cent and all unacclimatized persons lose useful consciousness within 10 minutes (TUC, the time of useful consciousness, is determined generally from the time of onset of hypoxia to the time when purposeful activity, such as the ability to don an oxygen mask, is lost). At 6 100 m (20 000 ft), the TUC is 10 minutes. (It should be mentioned that a given volume of gas at sea level doubles in volume when the pressure is dropped to that at approximately 5 500 m (18 000 ft).)

7) 7 600 m (25 000 ft): This altitude, and all those above it, produce a blood oxygen saturation below 60 per cent and a TUC of 2.5 minutes or less. Above this altitude, the occurrence of bends (nitrogen embolism) begins to be a threat.

8) 9 150 m (30 000 ft): The TUC is approximately 30 seconds.

9) 10 350 m (34 000 ft): The TUC is approximately 22 seconds. Provision of 100 per cent oxygen will produce a 95 per cent blood oxygen saturation (at 10 050 m (33 000 ft), a given volume of gas at sea level will have approximately quadrupled).

10) 11 300 m (37 000 ft): The TUC is approximately 18 seconds. Provision of 100 per cent oxygen will produce an oxygen saturation of approximately 89 per cent. When this altitude is exceeded, oxygen begins to leave the blood unless positive-pressure oxygen is supplied. (A given volume of gas approximately quintuples when the altitude changes from sea level to 11 600 m (38 000 ft).)

11) 13 700 m (45 000 ft): The TUC is approximately 15 seconds and positive-pressure oxygen is of decreasing practicality due to the increasing inability to exhale against the requisite oxygen pressure.

Table 2.— Effects of hypoxia at different altitudes

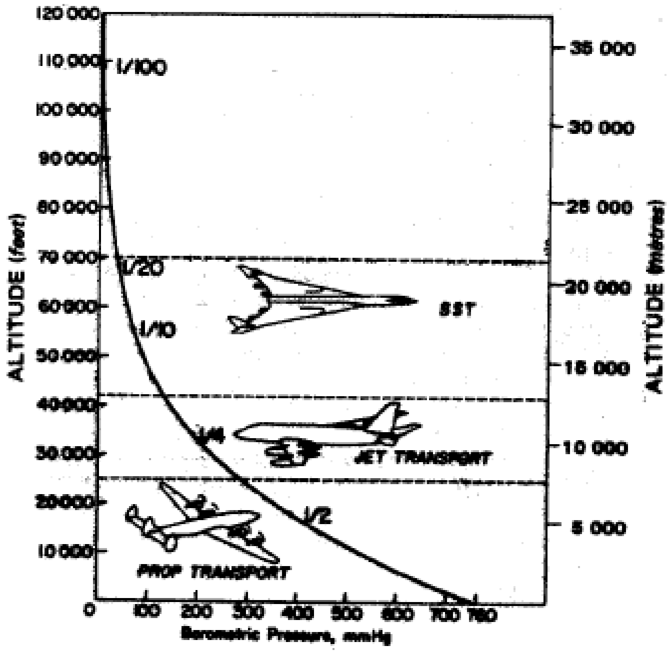

Figure 3.— Barometric pressure and altitude

A matter of practical importance is that barotrauma may occur at low altitudes because of the steep slope of the altitude pressure curve at lower levels. Even normal shifts in pressurized cabins can result in barotrauma since descent from only 2 000 m (6 500 ft) to sea level entails a pressure differential of 150 mm Hg.

Hypoxia

An important characteristic of biological significance of the flight environment is the decrease in partial pressure of oxygen with increasing altitude.

Hypoxia can for practical purposes be defined as decreased amounts of oxygen in organs and tissues, i.e. less than the physiologically "normal" amount.

In aviation medicine it is a subject of particular interest due to the fact that pressurized cabins are not usually maintained at sea-level values and therefore cabin pressures may add a moderate degree of hypoxia at altitude. Hypoxia has been the object of many studies, and several attempts have been made to classify and define its stages and varieties. A classification that has gained wide acceptance defining four varieties of hypoxia is as follows:

a) **Hypoxic hypoxia** is the result of a reduction in the oxygen tension in the arterial blood and hence in the capillary blood. It may be caused by low oxygen tension in the inspired air (hypobaric hypoxia) and is therefore of special significance when considering flight crew. Other causes are hypoventilatory states, impairment of gas exchange across the alveolar-capillary membrane, and ventilation-perfusion mismatches.

b) **Anaemic hypoxia** is the result of a reduction in the oxygen-carrying capacity of the blood. Decreased amount of haemoglobin available to carry oxygen may be caused by reduced erythrocyte count, reduced haemoglobin concentration, and synthesis of abnormal haemoglobin (e.g., sickle cell anaemia). Anaemia is an important consideration when assessing the advisability of air transportation for passengers with certain clinical entities.

c) **Ischaemic hypoxia** is the result of a reduction in blood flow through the tissues. It may be caused by obstruction of arterial supply by disease or trauma, and by general circulatory failure. Coronary artery disease is of major concern when assessing applicants for licences.

d) **Histotoxic hypoxia** is the result of an interference with the ability of the tissues to utilize a normal oxygen supply for oxidative processes. It may be caused by certain biochemical disorders as well as poisoning and may be of concern in crash survivability.

Subjective symptoms		*Objective signs*
Breathlessness; dyspnoea	INCREASING HYPOXIA ↓	Hyperpnoea or hyperventilation
Headache		Yawning
Dizziness (giddiness)		Tremor
Nausea		Sweating
Feeling of warmth about face		Pallor
Dimness of vision		Cyanosis
Blurring of vision		Drawn, anxious facies
Double vision (diplopia)		Tachycardia
Confusion; exhilaration		Bradycardia (dangerous)
Sleepiness		Poor judgement
Faintness		Slurred speech
Weakness		Incoordination
Stupor		Unconsciousness; convulsions

Table 3.— Signs and symptoms of hypoxia

In aviation, hypobaric hypoxia is by far the most common form of hypoxia. The symptoms produced in the body by hypoxia are both subjective and objective. Rarely are all the signs and symptoms found in any one person. Table 3 shows common signs and symptoms which might occur. It is difficult to state precisely at what altitude a given individual will react (i.e., show symptoms). The threshold of hypoxia is generally considered to be 1 000 m (3 300 ft) since no demonstrable physiological reaction to decreased atmospheric pressure has been reported below that altitude. In practice, however, a significant decrement in performance does not occur as low as that, but as altitude increases above that level the first detectable symptoms of hypoxia begin to appear and a more realistic threshold would be around 1 500 m (5 000 ft). Symptoms become more pronounced above 3 000 m (10 000 ft) which sets the limit for flight in unpressurized aircraft unless oxygen is carried on board. Pressurization systems are commonly designed to provide a physiologically adequate partial pressure of oxygen in the inspired air. In most passenger aircraft, the cabin pressure at cruising level corresponds to an ambient altitude of 1 500 to 2 450 m (5 000 to 8 000 feet).

PROTECTIVE SYSTEMS

Cabin pressurization

Cabin pressurization is one of the examples of technological solutions to a physiological problem in relation to aviation. In most modern commercial aircraft the problems of hypoxia and decompression symptoms are overcome by pressurizing the aircraft cabin to maintain a pressure that is compatible with normal physiological needs.

It would seem ideal to maintain sea-level pressure in an aircraft cabin at all times. This solution is usually impractical due to weight penalties and technical considerations. For these reasons, aircraft cabins are designed with pressure differentials which represent the compromise between the physiological ideal and optimal technological design. The pressurization characteristics of different commercial aircraft types are similar, with minor variations. In general, while the aircraft rate of climb might be in the order of 1000-3 000 ft/min (5-15 m/s) at lower altitudes, cabin altitude increases at a rate of about 500 ft/min (2.5 m/s) which represents an acceptable physiological compromise to equilibrate pressures within the body and the surrounding environment with a minimum of discomfort. On descent, the usual rate is no more than 300 ft/min (1.5 m/s).

The normal method of achieving cabin pressurization is by obtaining compressed air from the engine compressor, cooling it and leading it into the cabin. The pressure level is then set by controlling the rate of escape of the compressed air from the cabin by means of a barometrically operated relief valve.

Figure 4 indicates a typical pressure differential between the ambient altitude and cabin altitude for a commercial aircraft.

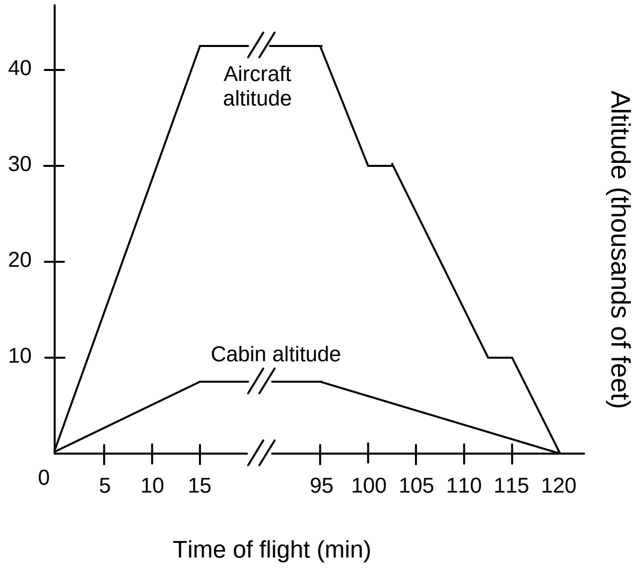

Figure 4.— Aircraft and cabin altitudes for a commercial aircraft during a typical flight[1]

DECOMPRESSION

All gases present in the body, either in free form in the cavities of the viscera or in solution in the body fluids, are in equilibrium with the external environment. Therefore, any changes in barometric pressure will give rise to transient pressure gradients between gases within the body and the external environment, and a gradient will persist until a new balance is reached. Depending upon the magnitude of the changing pressure and the rate at which it takes place, mechanical deformation and structural damage may occur on

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[1] Adapted from Rainford, D.J., Gradwell, D.P. eds. (2006)

decompression due to the relatively higher pressure of free gases trapped in body cavities.

In spite of all precautions, loss of cabin pressurization, including the remote event of rapid decompression, remains a potential hazard in the operation of pressurized aircraft at high altitudes.

Rapid decompression is an uncommon event in civil aviation operations. It may be produced as a result of structural failure or damage to the cabin wall (pressure hull). If it occurs, those on board might be exposed to the sudden onset of hypoxia for which oxygen equipment will be required. If the rate of decompression is of severe magnitude, organ and tissue damage may also ensue. Free gases in the body will expand. Cavities containing such gases are:

a) those with distensible walls;
b) those with free communication with the external environment; and
c) rigid or semi-rigid closed cavities.

The gases present in the distensible cavities, i.e. gastrointestinal tract, will expand under hypobaric conditions and may cause symptoms of discomfort and pain. Cavities with free communication will not give rise to complications as long as the size and patency of the communicating orifice and/or anatomical structure is adequate. Examples of these cavities are paranasal sinuses with open communication. The third type of cavities are those formed when a blocked paranasal sinus ostia or blocked Eustachian tube leading to the middle ear is present; they might give origin to pain of magnitude so severe as to be incapacitating.

Other forms of decompression manifestations are those produced by the evolution of bubbles from gases dissolved in blood and tissues - decompression sickness. In the context of civil aviation operations, this might occur when a person has been exposed to a hyperbaric environment, which has overcompressed inert gases in the body, prior to an ascent to altitude. Based on case studies and prospective investigations, the Undersea and Hyperbaric Medical Society recommends the following intervals between diving and flying:

Dive schedule		Minimum interval
1.	Non-decompression dives	
	a. Less than 2 hours accumulated dive time in the 48 hours preceding surfacing from the last dive	12 hours
	b. Multi-day, unlimited diving	24 hours
2.	Dives requiring decompression stops (but not including saturation dives)	24-48 hours

Table 4.— Recommended intervals between diving and flying

Further information concerning dive times and flying is available from the Professional Association of Diving Instructors (PADI) and the National Association of Underwater Instructors (NAUI).

Another important consideration in civil aviation operations is the possibility of slow decompression, including failure to pressurize during climb, which might occur as a result of failures of pressurization equipment, such as failure of an outflow valve, or incorrect settings of the flight deck pressurization controls by flight crew. If a slow loss of pressure occurs, the aircraft usually initiates a descent to a safer altitude; in some cases, on account of high ground, the aircraft is forced to continue flying at an altitude requiring oxygen. In such cases, the availability of oxygen systems is mandatory and if the planned route is over high ground that prevents an immediate descent to 10,000 feet or below, additional oxygen is required to be carried. When cabin pressure is lost, a barometrically triggered valve opens at a given cabin altitude - usually 10 000 - 14 000 ft (3 050 - 4 250 m) - and releases the masks for passengers. Passengers are briefed, prior to the flight, about the procedures to be taken to start breathing oxygen when required.

Other forms of decompression symptoms (dysbarisms) such as barotitis, barosinusitis and barodontalgia are further described in Part III, Chapter 12 of this manual.

COSMIC RADIATION

Radiation consists of a flow of atomic and subatomic particles and of waves, such as those that characterize heat rays, light rays, and X-rays. All matter is constantly bombarded with radiation of both types from cosmic and terrestrial sources.

Radiation can be ionizing (i.e. capable of turning atoms and molecules in matter and tissue penetrated into ions[2] and thus causing an electrical effect) or non-ionizing.

Cosmic radiation is the collective term used for radiation coming from the sun (the solar component) and from the galaxies of the universe (the galactic component).

Ionizing Radiation

Matter consists of a number of simple substances called elements which, as mixtures and compounds, form all the materials present on earth and in the universe. The basic unit of any element is the atom, and it is the characteristics of atoms that determine the properties of the elements.

Some elements are naturally radioactive, i.e. they change into other elements with the emission of atomic particles: radiation. Radiation may be thought of as energy in motion or as transfer of energy. When radiation energy is absorbed in living tissue, it may have a biological effect which depends not only on the amount of energy absorbed, but also on the specific effect of the wavelength and on the type of particles (electrons, neutrons, positrons, etc). If ionization takes place, it frequently results in chemical changes in matter and in living tissue. These changes may affect the behaviour of living cells and the organism may suffer obvious injury if enough cells are involved. Unlike light and heat, which are also forms of radiation, ionizing radiations cannot be directly detected by the body's senses, except that the dark-adapted eye, during the 5-6 hours of a transatlantic polar flight, may see a few flashes of light as cosmic rays directly ionize the retina.

Source and type of radiation

The ionizing radiation to which everyone on earth is exposed comes from the universe, partly from outer space (galactic radiation of constant intensity) and partly from the sun (solar radiation of increased intensity during solar flare activity). Furthermore, the earth itself produces ionizing radiation (of intensity varying with geographical location). Even food and drinking water are sources of ionizing radiation.

In addition to this natural background radiation which has existed for millions of years, there are

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[2] ion: an electrically charged atom or molecule.

modern man-made sources of ionizing radiation: building materials in houses, medical and dental X-ray examinations, radioactive cargoes, fall-out from atmospheric testing of nuclear weapons, and possibly nuclear power plants.

Unit of measurement

The effect of both electrons, α-particles and γ-radiation on living tissue is to cause ionization. The amount of radiation energy absorbed is measured in gray (Gy)[3], but as the biological effect depends not only on energy but also on the composition of the radiation (different particles etc.), it is necessary to weight the absorbed dose to obtain a dose equivalent, a unit of "harmful effect", called sievert (Sv).[4]

Background Radiation

Everybody on earth is exposed to radiation. The total normal radiation (background radiation) per person is virtually constant with a yearly dose equivalent estimated to be about 2 mSv in most countries. But due to natural radioactivity in soil and rocks, in parts of Brazil the yearly average is as high as 5-10 mSv, and in Kerala (India) a yearly dose of 28 mSv has been measured. In the industrial countries radiation from other sources, mainly medical X-rays, is estimated to around 1 mSv. On top of this exposure, totalling 3 mSv/year, may be added "occupational exposure".

Occupational Exposure

In recent years world-wide attention has been given to the problem of air crew being exposed to ionizing radiation. In the European Union, following the recommendations of the International Commission on Radiological Protection (ICRP), specific provisions on the health protection of air crew against dangers arising from exposure to cosmic radiation have been laid down in legislation since May 2000. There is, however, still some disagreement about the effects and even the amount of radiation to which air crew are exposed while on duty.

A substantial part of the cosmic radiation is absorbed by the upper part of the atmosphere or deflected by the earth's magnetic shield, but some penetrates to ground level and thus forms part of our natural environment. The intensity of cosmic radiation increases with height above sea level because the atmosphere becomes thinner and absorbs less of the radiation (e.g. the intensity of cosmic radiation is doubled by an increase in altitude from sea level to about 5000 feet and this doubling continues up to about 70 000 feet). High altitude flight therefore increases the degree of exposure to cosmic radiation. The polar regions have a greater radiation intensity than the equatorial regions, owing to flattening of the atmosphere over the poles and the shape of the earth's magnetic field.

Many studies have been conducted aboard airliners, mainly flying on North Atlantic routes, to establish the amount of radiation to which the air crew are exposed. Based on these studies, it is possible to <u>calculate</u> a radiation exposure of approximately 5 mSv per year for air crew flying 600 hours per year north of N50 at altitudes above 39 000', and approximately 3.3 mSv per year if the flight level is reduced to altitudes around 33 000'. If the annual flying hours are calculated for cruising only (with deduction for start, climb, descent, and landing) to 400 hours per year, the radiation exposure will be around 2 mSv. Flying south of N50 will entail a further reduction in exposure.

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[3] 1 Gy = 1 joule/kg = 100 rad (absorbed radiation).

[4] 1 Sv = 1 joule/kg = 100 rem
(dose equivalent = 1 Gy for β-radiation).

In a recent study conducted by the national airline in a Contracting State, situated between N60 and N70, the maximum radiation exposure in full-time air crew measured during ordinary scheduled flying over one year was 2.8 mSv.

Maximum Exposure

The maximum radiation exposure, recommended by ICRP, for individual members of the public is 1 mSv per year or, in particular cases, 5 mSv per 5 years. For workers exposed to radiation (and therefore under special surveillance which may include annual health examinations) the recommended limit is 100 mSv per five years or an average of 20 mSv per year with a maximum of 50 mSv in any one year. For pregnant workers the recommended limit is 1 mSv per year or the same for the foetus as for any other individual member of the general public.

Use of Computer Programmes to Estimate Dose

It is possible to estimate the radiation dose for a certain route by using a computer programme developed for this purpose. The data to be input are the date and location of departure, the flight profile, detailing the time in climb, cruise and descent, and the time and location of arrival.

One such programme, which is simple to use and has been validated, is produced by the Civil Aeromedical Institute (CAMI) in the United States. CAMI was previously known as the Civil Aeromedical Research Institute (CARI). The latest version of this computer programme is called CARI-6 (dated 7 July 2004). It can be down-loaded from CAMI's website or accessed on-line at http://jag.cami.jccbi.gov./cariprofile.asp. A similar European programme, EPCARD (European Program Package for the Calculation of Aviation Route Doses), has been developed and is available on-line in English and German at www.gsf.de/epcard2/index.phtml.

Risk Assessment

Ionization can cause chemical changes in living tissue and may thus affect the behaviour of living cells. This can lead to cell death (as in acute radiation sickness) or to alteration of genetic material within the cell (so-called mutation as seen in late sequels). The latter can induce cancer or lead to anatomical defects in a foetus. These effects, however, are dose related: low doses of radiation carry a low risk, and the lower the radiation dose is, the longer is the interval from exposure to development of disease, often many years.

We have no exact knowledge about the risk of low dose radiation, but studies of the survivors from the Hiroshima and Nagasaki atomic bombings in 1945 indicate that a radiation dose of 500 mSv leads to development of cancer in about 1% of those exposed. Consequently, according to the theory of linearity, a radiation dose of 1 mSv entails a cancer risk of 0.002% (1 mSv is about 1/3 of the natural background radiation, *vide supra*). With few exceptions the incidence of cancer has not been increased detectably by doses of less than 100 mSv.

It is generally estimated that 1.5% of all fatal cancers in the general population result from natural background ionizing radiation. A man, living on Earth for 70 years, will receive a total dose of ionizing radiation of about 210 mSv. His risk of developing a cancer due to radiation is about 0.42% or one in 238. If he flies as an airline pilot for 40 years he may receive an additional dose of some 112 mSv which entails an additional cancer risk of about 0.22%. The over-all risk of acquiring a fatal cancer disease (all types, all causes) during a lifetime is about 22% (including 0.42% caused by radiation). The airman's total risk will thus rise from about 22% to about 22.2%. In other words: if one thousand airmen have a normal flying career, the expectation is that two of them would eventually die of cancer as a result of occupational exposure to radiation. Based on normal expectation for the adult population, about an additional 220 of the 1000 airmen would die of cancer from causes unrelated to occupational radiation exposure. There is, of course, no way of telling whether a specific cancer is caused by background radiation, occupational radiation or other factors.

A liveborn child conceived after radiation exposure of its parents is at risk of inheriting a genetic defect that may lead to a serious health impairment. From each parent's exposure, the risk coefficient is 1.5 in 1 000 000 per mSv. If a female crewmember works for ten years and thus is exposed to an additional 28 mSv, the risk to the child as a result of work related exposure to radiation would be approximately 28 x 1.5 = 42 in 1 000 000. In the general population about 6% (or 60 000 in 1 000 000) of the children are born with anomalies that have serious health consequences. In other words: if 23 800 children were born after occupational radiation exposure of their mothers, one of them would have a congenital genetic defect or eventually develop a genetic disease as a result of his mother's occupational exposure to radiation. Based on the normal expectation for newborn children, an additional 1428 children of the 23 800 would have genetic defects from other causes.

Recommendations

In view of the fact that ionizing radiation is now assumed to play a role in mutagenic or carcinogenic activity, any procedure involving radiation exposure is considered to entail some degree of risk. At the same time, however, the radiation-induced risks associated with flying are very small in comparison with other risks encountered in daily life. Nevertheless such risks are not necessarily acceptable if they can be easily avoided.

Theoretically, the radiation exposure in air crew can be reduced by optimizing flight routes and crew scheduling, and by installation of radiation warning devices[5]. Such devices are particularly effective in detecting high momentary radiation during solar flares and can thus be used in determining a need for a lower cruising level. Female crew members should be aware of the possible risk to the foetus and should be scheduled in such a way as to minimize the exposure during pregnancy.

Much study has been directed to the potential hazards of cosmic radiation (CR) to flight crews and passengers of supersonic transport (SST) aircraft. Measurements show that in the high latitudes above 50N the maximum total body dosage at 65 000 ft (~20 000 m) – an altitude approximating the cruise altitude of SST aircraft - is about 0.013 mSv/hour. Because of the reduced journey time the dosage per unit of distance traveled is about the same as in current subsonic jets where 0.005 mSv/hour is recorded during flights at about 37 000 ft (11 000 m) and at latitudes around 45EN. CR is not therefore expected to be significantly more hazardous to the flight crews and passengers of SST aircraft, as even if the mileage flown by crews were to be doubled, the effects of CR would not be regarded as harmful. As previously stated, Annex 6, Part I, (paragraphs 6.12 and 11.1.17) contains provisions concerning radiation monitoring in aeroplanes operated above 49 000 ft (15 000 m).

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[5] A radiation warning device (an in-flight radiation dosimeter) was used in the Anglo-French supersonic transport (SST) aircraft *Concorde*. This device provided a continuous display of the radiation dose rate.

OZONE

Ozone is triatomic oxygen, O_3. Stratospheric ozone is formed by the action of ultraviolet light on oxygen ($3\ O_2 > 2\ O_3$). It is found in varying quantities, the peak values being recorded at about 35 000 m (115 000 ft) with negligible values at or below 12 200 m (40 000 ft) and much reduced levels above 42 700 m (140 000 ft). The cruise altitude of commercial SST aircraft in northern latitudes, about 18 450 m (60 000 ft), could produce levels of ozone of 2 000-4 000 $\mu g/m^3$ (1-2 parts per million (ppm)). Ozone is destroyed by heat, by the catalytic action of some materials including nickel and by organic compounds. Total destruction occurs at 400°C (750°F). Air in the cabin pressurization system of one type of SST (when SST public transport operations were undertaken) is heated to 600°C (1 120°F) and this heat is utilized to destroy ozone. However, it has been reported that when engine power is reduced to initiate descent, this manoeuvre is accompanied by a fall in the temperature of the cabin pressurization system which could permit a potential buildup of ozone. During descent, levels of 400-1 000 $\mu g/m^3$ (0.2-0.5 ppm) may be experienced for about ten minutes within the pressurized section of the aircraft. The existing data on the health effects of ozone, considered in conjunction with its high natural background level, lead to the recommendation of a 1-hour guideline in the range of 150-200 $\mu g/m^3$ (0.076-0.1 ppm). To lessen the potential for adverse acute and chronic effects and to provide an additional margin of protection, an 8-hour guideline for exposure to ozone of 100-120 $\mu g/m^3$ (0.05-0.06 ppm) is recommended by the World Health Organization (WHO). Tests, based on the exposure concentrations and time intervals calculated for SST aircraft, have been conducted by the Medical Research Council of the United Kingdom and showed no significant functional impairment. Although the original research concerning ozone and aviation was undertaken for SST operations, catalytic converters were recommended by the UK House of Lords Select Committee on Science and Technology to be fitted to subsonic aircraft when they could be expected to fly through higher concentrations of ozone. Such equipment is now standard on many modern aircraft.

ACCELERATION EFFECTS

Short-term accelerations

Speed itself in straight and level flight has no effect on the human body; accelerations due to changing speed and/or direction of flight may, on the other hand, produce very considerable physiological effects upon the occupants of an aircraft depending on the following factors:

a) magnitude, rate and direction of acceleration;
b) duration;
c) area of application; and
d) protection.

Accelerations of relatively short duration, usually less than a second, are associated with situations such as flying in turbulence or emergencies such as crash landings. The critical protective factor for short-term accelerations and rapid decelerations is the availability of restraint systems. The desirability of shoulder harnesses for flight crew has been documented, taking into account not only crash protection but also the possibility of on-duty incapacitation of a kind that might interfere with the operation of flight controls.

The reader is referred to other texts for information relating to long-duration accelerations and other aspects relevant to in-flight acceleration. Acceleration effects may result in sensory illusions (see below).

SENSORY ILLUSIONS

The sensory perceptors of the human body associated primarily with maintaining equilibrium and orientation are the eyes, the inner ears and proprioceptors in muscles, tendons and joint capsules. Their coordinated action plus the mental integration of all their messages establish a reference which keeps human beings upright and oriented in relation to the direction of the gravitational force.

The eye is a very reliable orientation mechanism provided adequate reference points are available. When flying, however, there are disadvantages in trying to interpret visual clues. Objects seen from the air often look quite different from objects seen from the ground. In the air, there is also a lack of visual clues that a continuous background provides for recognition of objects and assessment of their size and distance.

Visual illusions in flight may be caused by any of the following factors:

a) Optical characteristics of windshields
b) Rain on windshields
c) Fog, haze, dust and their effects on depth perception
d) Glide slope
e) Width and length of runway
f) Runway lighting systems
g) Runway slope
h) Terrain slope
i) Landing at night over water or other unlit terrain
j) Auto-kinetic illusion
k) White-out, specifically in high-latitude areas.

The semicircular canals are associated with equilibrium. Angular movement or rotation of the body moves the fluid of the semicircular canal, thereby causing displacement of the cupulae covering the hair cells in the ampullae. Impulses are transmitted to the brain and interpreted as motion. Since each one of the three semicircular canals lies in a different plane, they can report rotation in three planes. The normal mode of stimulation for these organs is an abrupt, short-duration acceleration followed immediately by a short deceleration.

It must be remembered that the semicircular canals provide information only about angular movements of the head. Sensations of relative motion and relative position of body parts are supplied by perceptors in the skin, joints and muscles. Otoliths provide information about position.

Humans normally depend on the complex integration of the three above-mentioned sensory inputs, i.e. eyes, inner ear and proprioceptors, for the perception of the body's relationships to terrestrial references.

The following are common examples of disorientation in flight:

a) In a horizontal turn, the illusion of continued straight flight may be experienced if the rate of turn is too low to stimulate the semicircular canals.
b) The subjective impression of angle of bank during instrument flying is false when the angular change is introduced gradually and below the thresholds of stimulation of the semicircular canals and proprioceptors.
c) The "graveyard spiral" results when, in a prolonged (> 20 seconds), coordinated banked turn the cupulae come to rest and the sensation of turning is lost. When leveling the wings, the pilot may experience a sensation of now turning to the opposite side. To counter-act this sensation of

turning, the pilot may re-enter the original turn. Because the instruments indicate loss of altitude, the pilot may pull back on the stick and add power, thus making the turn tighter (increasing the bank) and inducing the spiral.

d) The somatogravic illusion is caused by the effect of acceleration on the otolith organ. When deprived of visual input from the surrounding world (for example taking-off in IMC[6]), a pilot may interpret accelerative forces ($+G_X$[7]) as a nose high attitude of his aircraft, correct this false sensation by pushing the stick forward and may thus fly his aircraft into the ground.

A further elaboration on disorientation in flight, as well as vertigo, is contained in Part III, Chapters 10 and 12.

COMMUNICATIONS

The importance of the communication system in present-day civil aviation operations cannot be overemphasized. Speech intelligibility and communication are vital elements in the safety of civil aviation. In order to start the engine, taxi the aircraft, line up for take-off, get clearance for take- off, start climbing procedures, reach cruising level, or to initiate the sequence of events that will lead to the safe approach and landing of the aircraft at the destination, a licence holder must be able to transmit and receive verbal instructions to and from the air traffic control system as well as from the crew complement. In this particular respect, account should be taken not only of the physiological speech intelligibility in noisy surroundings, but also of the aspect of hearing under operational conditions, when the attention is required to encompass a multiplicity of stimuli which are of paramount importance.

Interference with intelligibility and speech communication is a potentially serious problem which can be brought about by higher levels of noise at certain frequencies. This problem can prevent crew members from communicating with each other, whether directly or by means of an intercommunication system ("intercom"), and can also interfere with voice communication between ground and aircraft. When sound pressure levels within cockpits and communication systems rise, the voice must be raised in order to communicate against the noisy background, and if the interference becomes excessive, speech intelligibility becomes adversely affected or lost altogether. This is auditory masking or "drowning out" by noise; it lasts only whilst the noise is present. It represents the inability of the auditory system to separate the different tonal components, and tends to be worse when the conflicting frequencies are similar.

Apart from controlling noise sources, efforts must also be made to limit the entry of noise into the communication system. The position can be further improved by selecting the best possible characteristics for a communication system and by the use of special vocabularies (as standard ICAO phraseology for Aeronautical Telecommunications, described in detail in Annex 10, Volume 2, Chapter 5). Apart from engine and aerodynamic sources, noise can be generated by the cabin air conditioning system, by electronic equipment within the cockpit, by certain types of oxygen regulators, and by the individual's breathing into a "live" microphone. The degree of interference will depend upon the relative frequencies and strengths of the voice or tone signal and the ambient noise level.

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[6] IMC: Instrument Meteorological Conditions, i.e. weather with reduced visibility where only flying in accordance with the Instrument Flight Rules (IFR) is allowed.

[7] +Gx: Acceleration (G) is a change in velocity either in direction or in magnitude. It is described in three axes in relation to the human body, x, y and z. Each axis is described as positive (+) or negative (–). **+Gx** is a forward acceleration with a transverse anterior-posterior (chest to back) resultant force.

To guide the medical examiner in the proper assessment of applicants for medical certification, speech tests in neutral noise as well as aviation noise have been described elsewhere in this manual (see Part III, Chapter 11).

FLIGHT CREW WORKLOAD AND ITS EFFECTS ON PERFORMANCE

Fatigue

Many working and environmental conditions lead to fatigue, affecting people in a multiplicity of ways. Individual responses to fatigue are significantly different.

Fatigue may be transient and/or cumulative. Transient fatigue is normally experienced by a healthy individual following a period of work, exertion or excitement, and it is normally alleviated by a single period of sleep. Cumulative fatigue may occur after delayed or incomplete recovery or as the after-effect of more than normal amounts of work, exertion or excitement without sufficient recuperation.

Workload fatigue, as it affects flight crews, may have a significant effect in reducing performance. Some of the causes contributing to workload fatigue are the cockpit layout, the hours of work and other specific factors as follows: beginning and end of last flight, duration of rest time between present and last flight, duration of sleep during this rest period, the time of commencement of pre-flight briefing, problems arising during briefing, delays preceding departure, timing of flights, meteorological conditions, quality and quantity of radio communication, visibility during descent, glare and protection from sun, turbulence, and technical and personal problems. One Contracting State found that what flight crew described as “hassle”, meaning anything that caused a non-routine situation, was fatiguing.

Continuous technological developments are being pursued; seating, instrumentation, lighting, cockpit design, climatic conditions in the cabin and radio communications equipment are being further improved.

An important contributing factor to fatigue in aviation operations is the disruption of circadian rhythms. Time zone displacements without sufficient adjustment time might seriously impair the performance of personnel engaged in aviation duties. Many organic functions are periodic - their rhythm determined by both internal and external phenomena - for instance sleep-wake cycles, respiration, body temperature, endocrine functions and physical and psychological performance. All these functions show a 24-hour cyclic pattern. Transmeridian flights crossing time zones affect the specific patterns and periodicity for travellers.

One of the most common causes of fatigue in aviation has to do with the scheduling of flight crews. Mental and physical conditions might influence the appearance and severity of fatigue, the end result being a lowered efficiency and impaired performance.

In this particular connection, care should be taken by appropriate authorities to ensure that good quality rest facilities are provided for air crew at stations away from their bases. This is an important measure to diminish the effects of fatigue.

Several self-imposed stresses can be mentioned as contributory causes leading to fatigue: of paramount importance in this respect are drugs, alcohol, tobacco, poor sleep hygiene, inadequate diet, and the general state of health of the licence holder.

Consideration should be given not only to the routine operational conditions, but also to those situations when there is an increased demand for mental and physical ability to cope with emergency situations and periods of peak workloads (e.g. missed approach, aborted take-off and, for ATC officers, high density towers, heavy traffic).

Particular reference is made in the above considerations to results of studies showing that a fatigued pilot can concentrate effectively enough on a principal task but has reduced ability to cope with extra stimuli or secondary tasks which may arise.

To ensure that fatigue of licence holders does not endanger the safety of a flight, regulatory documents specify limitations of flight time and flight duty periods (see further Part I, Chapter 1). However, it is true to say that prevention of fatigue is an issue that requires further work by many regulatory authorities.

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