CHAPTER 3

PHYSIOLOGICAL EFFECTS OF ACCELERATION

CONTENTS

Introduction

1. Speed, even at very high values, has no effect on the human body. On the other hand, inertial forces resulting from changes of velocity in either magnitude or direction, may produce very considerable effects. The effects of such accelerations on the body depend on the following factors:

 a. Magnitude of the acceleration.

 b. Duration of the acceleration.

 c. Direction of the acceleration.

 d. Site of action of the acceleration.

 e. In some cases, the rate of application of the acceleration, or jolt, may be significant.

2. The direction of action of acceleration is defined on a three co-ordinate system based on the human spine, where Z is the vertical axis, X the fore and aft axis and Y the lateral axis. Positive and negative signs are used to specify direction along each axis such that a headwards acceleration is $+g_z$, a forwards acceleration is $+g_x$ and a right lateral acceleration is $+g_y$. Footwards, backwards and left lateral accelerations, therefore, become $-g_z$, $-g_x$ and $-g_y$ respectively.

3. It is important to note that the force which is sensed, and tends to displace the body, or if restrained, components of the body, is the inertial reaction. This reaction is at all times equal in magnitude, but opposite in sign to the applied acceleration. Thus, a headwards acceleration ($+g_z$) tends to force the body down onto the seat and to displace blood towards the feet. The astronauts notation for different acceleration vectors such as eyeballs down for $+g_z$, eyeballs out for $-g_x$, etc, is based logically on the direction of this inertial reaction.

4. Accelerations are usually measured in units of earth's gravity, $1g$ being the force required to accelerate a body at approximately $9{\cdot}8\,\text{m/s}^2$ ($32\ \text{f/s}^2$). The three types of acceleration to be considered are:

 a. Linear acceleration caused by change in speed.

 b. Radial acceleration caused by change in direction.

 c. Angular acceleration caused by change in rate of rotation.

5. The folowing is a brief summary of the chief accelerations which can occur in flight or are otherwise relevant to aviation:

 a. *Linear*:

  (1) Catapult or rocket assisted take-off ($+g_x$).

  (2) Arrested landings, barrier engagements ($-g_x$).

  (3) Crashes, crash landings, ditching (initially $-g_x$).

  (4) Buffeting (predominantly $\pm g_z$).

  (5) Seat ejection (initially $+g_z$).

  (6) Parachute opening shock and landing by parachute (predominantly $+g_z$).

b. *Radial.* These are accelerations caused by rotation about a distant axis. They act outwards from the centre of rotation and are experienced whenever an aircraft changes direction.

c. *Angular*. Angular accelerations are experienced if the rate of rotation changes, or if a second axis of rotation is added to the first. The principal effects on the body are those related to the vestibular apparatus (organ of balance) and it is convenient to discuss these separately. (*See* Chapter 4).

Effects of Linear Acceleration

6. Linear accelerations result from an increase of speed (take-off), and decelerations from a decrease of speed (landings and crashes). The problems associated with buffeting and seat ejection are dealt with in paras 14-20.

7. During catapult assisted take-off, an acceleration of $+4g_x$ may be expected, and a rather lesser deceleration of $-3g_x$ may occur during an arrested landing. In wheels up landings or ditchings, the force may exceed $-10g_x$, and in crashes may exceed $-25g_x$. Linear forces encountered in aviation usually last for less than one second, though prolonged linear accelerations are imposed during the launching and re-entry of space vehicles. The problems associated with sustained forces will be discussed more fully when dealing with radial accelerations.

8. It has been shown that the human body, properly supported, can tolerate a very much greater acceleration than any aircraft structure. In rocket sledge experiments values of $+40g_x$ have been imposed on the human body without injury. Values as great as $+60g_x$ have been reached with survivable injuries. In general, it is not necessary to provide protection against accelerations higher than $\pm 25g_x$ since values as great as this will only be attained in disastrous, uncontrolled crashes involving massive structural disintegration of the aircraft.

9. It is clear that the problem associated with high accelerative forces of relatively short duration is one of body restraint and also, in particular cases, body posture. This latter criterion is of immense importance in the use of ejection seats, under which heading it will be discussed.

10. During crash deceleration in a forward facing seat ($-g_x$), an unrestrained occupant may be flung forward and injured or killed by striking solid objects in front of him. Even low decelerative forces have produced fatal results in road traffic accidents. The simplest form of restraint is the lap belt, but this is not satisfactory as it does not prevent the body flexing at the hips, thereby permitting the head to move forward and strike any solid object in its path. Also this sharp forward flexion at the hips is liable to cause fractures at the lower end of the spine. Furthermore, since the area of restraint provided by the lap belt is small, the associated high contact pressure is liable to cause internal abdominal injuries.

11. The conventional seat harness in an aircraft has both a lap belt and shoulder straps. The restraint afforded by the lap belt across the thighs is intended to reduce both vertical and forward movement of the hips, and the shoulder harness is designed to prevent forward flexion during $-g_x$ acceleration. A 'negative-g strap' attaching the harness quick release fitting to the front of the seat pan may be used to provide a greater reduction in vertical movement than can be achieved with the conventional harness. The head is unrestrained and forward flexion of the neck is likely to occur in crash decelerations. In order to prevent damage to the head, effort is made during cockpit design to ensure a clear path for a distance of 16 inches in front of the head. Further protection is, of course, provided by a well fitting helmet.

12. Standard RAF harnesses protect the wearer against forward decelerations of up to $25g$, provided that they are properly fitted, tight, and with the lap belt as low as possible and shoulder straps locked. A high lap strap could allow the wearer to slip forwards underneath the harness during forward decelerations. Seat and harness attachments must also be stressed to $25g$. In cases where there is a separate parachute quick release fitting, it should be located higher than the seat harness quick release fitting, otherwise it could be driven back by the second fitting and possibly cause internal injury.

13. In passenger aircraft, it is difficult to provide the occupants with a safety harness which will give adequate restraint and, at the same time, reasonable freedom of movement and comfort. The policy of the RAF has been, therefore, to fit military transport aircraft with rearward facing seats so that in the event of a crash the body will be supported and restrained by the entire seat area. Thus, the

crash deceleration becomes $+g_x$. A head rest is essential to prevent neck injury and the seat, its floor attachments and the floor structure must be of sufficient strength to prevent the seat from breaking loose. The passenger seat is fitted with a simple lap belt to restrain the occupant in turbulence and in the event of other axes of acceleration occurring during crashes. Also the head rest should have forward projections at each side to provide lateral restraint. Rearward facing seats have proved very successful during major aircraft accidents.

Buffeting

14. Vibrations occur during flight for a number of reasons, but most significant in relation to harness restraint is the buffeting which can occur when an aircraft flies fast in turbulent conditions—in cloud, over mountains, or a low level; particularly in hot climates, or over uneven terrain. These rapidly alternating vertical accelerations are usually of the order of $\pm 1{\cdot}5$ to $2g_z$, but occasionally values as great as $\pm 3g_z$ may occur. They are governed in amplitude and frequency by the speed and wing loading of the aircraft, as well as by the amount of turbulence. One of their effects is to hasten the onset of fatigue in the individual, but if of sufficient amplitude they may make control difficult or even cause an inadequately restrained occupant to strike his head against the cockpit canopy or cabin roof. At certain frequencies, buffet accelerations may interfere with vision. The wearing of a protective helmet in addition to a properly tightened harness prevents head injury and it is the duty of captains to ensure that they and their crews and passengers have their harnesses secure when there is a possibility of flying into turbulent conditions.

Seat Ejection

15. In order to clear high tail structures and also give a low level escape capability, the ejection gun has to provide the highest possible velocity, and hence gain in altitude, without exceeding the acceleration tolerance of the seat occupant. Early investigations showed that not only was there a limit to the peak acceleration which could be employed, but there was also a limit to the rate at which this acceleration could be applied. It was established that the absolute limit of human tolerance to ejection was $+25g_z$ and that at no time must the rate of rise of g exceed 300 g/s.

16. Ejection acceleration loads depend not only upon the energy of the gun system and weight of the seat and occupant, but also upon the transmission of energy from the seat to the man. This transmission is influenced by the elastic properties of equipment stowed in the seat pan, as well as by the dynamic response of the occupant, and it is essential that no unauthorised equipment should be placed in the seat pan, nor should the contents of survival packs or cushions be altered in any way.

17. Due to the dynamic response, the acceleration rise time (time to peak g) should be greater than the undamped natural period of the man/seat system. This implies a rate of rise of acceleration, ideally, no greater than $125g/\text{s}$. However, this may be exceeded if the peak acceleration is significantly less than $24g$. It is now possible to analyse complex acceleration profiles by computer to obtain a measure of the maximum stress induced in the spine (the usual point of failure if ejection tolerance is exceeded). This, the so called Dynamic Response Index (DRI) may then be used to predict the risk of spinal compression fracture.

18. To overcome the limitations of performance imposed by human tolerance to acceleration, rocket assisted seats may be used. The advantage of rocket assistance is that it permits a longer application of thrust; lower peak loads and rates of onset of acceleration may therefore be employed whilst permitting even greater trajectories to be achieved.

19. In order to permit the body to take maximum advantage of the ejection seat facilities without injury, it is essential to ensure a good posture and a high degree of restraint by means of a well tightened harness assembly. In this way the thrust is directed along the line of the spine and any dangerous bending moment is reduced.

20. After ejection, particularly at high indicated air speeds, further accelerations will be experienced, some of which may be associated with a seat tumbling or deceleration resulting from the deployment of stabilising equipment. Detailed considerations of these matters will be found in the chapter dealing with aircraft abandonment.

Parachute Opening Shock

21. High accelerations may be experienced on parachute deployment, the opening shock load increasing with air speed or altitude. At 7,000 ft the opening shock load for a 7 m (24 ft) canopy has been quoted at approximately $9g$ whereas at 42,000 ft this same canopy would give an opening shock load of about $32g$. An opening shock load as high as this would

almost always cause severe damage to the canopy and also to the subject. For this reason alone, it is undesirable to permit canopy deployment much above 20,000 ft, quite apart from the fact that a delayed opening reduces the time spent at high altitude, where the problems of oxygen lack and low temperature would be significant.

Parachute Landing

22. The deceleration experienced during parachute landing is very variable, depending on the parachute, the man, his landing attitude and the terrain. The average aircrew member is not skilled nor practised in actual parachute landing, but it is important to ensure that the situation is not aggravated by increasing the rate of descent in attempting to carry out difficult parachuting manoeuvres near the ground. Some new parachutes produce a horizontal velocity component, or drive, of several metres per second. This allows a smaller canopy to give an acceptably low descent rate and also damps out instability so that landing should be more controlled.

Effects of $+g_z$ Acceleration

23. In the 1929 Schneider Trophy Race, competitors reported visual troubles and confusion while rounding the pylon. These symptoms were caused by $+g_z$ accelerations arising from the speed and manoeuvreability of the aircraft.

24. Radial accelerations are most commonly experienced in turns, especially in high-performance aircraft. The formula relating accelerative force (F) to velocity (V) radius of turn (r) and the mass of the aircraft (M) is as follows:

$$F = \frac{MV^2}{r}$$

From this formula it can be seen that doubling the velocity of flight along a curved path quadruples the force applied to the aircraft and crew, while halving the radius of turn doubles the force. This increased force, measured in units of *g*, is felt by the subject as an increase in weight, weight being equal to mass times acceleration.

25. Under increased $+g_z$ acceleration the effective weight of the whole body and its components (especially the blood) is increased with the following effects:

a. Fluid and tissues are displaced downwards. This is most apparent in the face where the skin can be seen to sag.

b. Since the effective weight of the body may be increased many times, whereas the power of the muscles remain unaltered, movements become progressively more difficult. If the head is lowered, it may not be possible to raise it again, especially if a heavy helmet is worn. At $+2{\cdot}5g_z$ it is almost impossible to rise from the sitting position and unaided escape from an aircraft would be virtually impossible. At $+4g_z$ it is just possible to raise a hand to the ejection blind, but at any greater level of acceleration the seat pan handle would have to be employed.

c. The blood becomes heavier and tends to drain from the upper parts of the body and to collect in the abdomen and lower limbs. The failure of the blood to return to the heart in the normal way means that the supply of blood available for re-oxygenation in the lungs and subsequent distribution round the body is reduced.

d. The pressure drop in the blood circulation from heart to brain due to gravity is increased, and in addition the heart is displaced downwards under its increased weight, so lengthening the vertical column of blood between heart and brain.

26. As a result of these circulatory disturbances, the eye and brain are starved of oxygen. As the level of acceleration is increased, partial loss of vision (grey-out) occurs, followed by total loss of vision (black-out) and eventually loss of consciousness if the manoeuvre is sustained. Loss of vision begins on the outside of the visual field and gradually moves into the centre, so that the grey-out phase has been likened to looking down a foggy tunnel. The reason for visual disturbance occurring before loss of consciousness can be explained in simple mechanical terms. The pressure needed to supply the eye with blood is greater than that required to supply the brain, because the eyeball has a positive internal pressure. Thus, the fall in blood pressure at head level which results from $+g_z$ acceleration first affects the blood supply to the retina and produces impairment of vision.

27. As in many other situations, the body makes some attempt to compensate for these changes. If a level of acceleration which first produced grey-out is maintained, it is likely that vision will return to normal. This is due to a reflex diversion of blood from some regions to maintain a satisfactory supply to more important tissues such as the eye, heart and brain. Similarly, black-out may improve to grey-out

or normal vision may be recovered. Loss of consciousness indicates a failure of this compensatory process, or may occur if the onset of acceleration is so rapid that tolerance is exceeded before the reflex mechanisms can act.

28. The severity of these effects is not solely dependent upon the level of acceleration; the duration of exposure is a significant factor. Brief exposures to high levels of acceleration may cause loss of control, or even damage to the aircraft, but will not have time to cause circulatory disturbances. The significance of the time factor can also be seen during the pull-out from a dive where symptoms are likely to occur towards the end of the manoeuvre. Therefore, in describing levels of normal response to $+g_z$ acceleration, it is necessary to define both the level of acceleration and its duration.

29. An acceleration of +3 to $+4g_z$ acting for 3-6 seconds is sufficient to cause some reduction in peripheral vision. Plus 4 to $+5g_z$ acting for 6 to 10 seconds may produce black-out or even loss of consciousness. These levels can vary widely from individual to individual, or even in the same person depending upon extraneous factors such as hunger, alcohol, concurrent illness, fatigue or hypoxia. In general, the grey-out threshold is about 1*g* below the black-out threshold, and this in turn about 1*g* below the threshold for unconsciousness. The range is wide, however, and unconsciousness has been encountered as low as $+3g_z$.

30. The effects of black-out disappear as soon as the *g* level is reduced although, for a few seconds, there may be some difficulty in focusing the eyes. Loss of consciousness may be followed by confusion for up to 30 seconds so care should be taken not to proceed beyond the black-out stage even momentarily, especially if the handling of the aircraft is critical. Recovery from unconsciousness is frequently associated with jerky and uncontrolled movements of the head and limbs; while of no clinical significance, these movements may interfere with the control of the aircraft.

31. Repeated exposures to $+g_z$ while breathing 100% oxygen may lead to a condition of 'acceleration atelectasis' in which the lower parts of the lungs become solid and give rise to shortness of breath, cough, chest pain and difficulty in taking a deep breath. The condition is most likely to occur when an anti-*g* suit is worn. It is due to the lower lung being compressed against the diaphragm by the weight of overlying lung. Ventilation of the compressed region is prevented and the trapped gas is rapidly absorbed so that the tissue becomes solid. The condition may be prevented by the use of the airmix (nitrogen being so poorly soluble that the absorption of the trapped gas is never complete), and can be readily corrected by taking deep breaths after each exposure to acceleration.

Increasing Tolerance to *g*

32. Since the more serious consequences of high levels of positive acceleration are circulatory in origin, it follows that efforts to support the circulation will increase tolerance to *g*. Support can be provided in three ways:

a. *Position*. Suitable alterations in posture can reduce the vertical heart-to-brain distance and thereby improve the efficiency of the circulation to the eye and brain. Thus, crouching forwards can increase the black-out threshold by nearly 1*g*. Further improvement can be obtained by raising the lower limbs and so aiding the return of blood to the heart. This position has been achieved in some aircraft by the provision of a high rudder pedal position to be used in combat manoeuvres. Tolerance to *g* can be further increased by tilting the seat backwards or by placing the subject in a prone or supine position. While tolerance would rise markedly there are problems with cockpit design, external view and ejection, which have so far prevented the use of such postures in RAF aircraft.

b. *Voluntary manoeuvres*. The normal mechanism for propelling blood along the viens and back to the heart is by the squeezing action of surrounding muscles. Tensing of muscles in the calf and thigh is therefore beneficial. Once returned to the abdomen, the displaced blood can be further propelled towards the heart by straining the abdominal muscles to raise abdominal pressure. However, if maintained for too long, this procedure will prevent more blood from entering the abdomen, and the process has to be made intermittent. Raising the pressure within the chest, as by shouting, or by attempting to breath out against a partially closed glottis (top of the windpipe), will increase the output of the heart and raise the blood pressure, but again the benefit is transient, a prolonged effort impeding further return of blood to the heart. Many of these practices become automatic to experienced aircrew who often have a higher tolerance to acceleration than inexperienced subjects. The individual piloting the aircraft is also likely to have a higher black-out threshold than his passenger, since he is in a position to anticipate the required actions. The muscular effort involved may also be beneficial.

c. *Anti-g suits*. An anti-*g* suit is now standard equipment in high-performance aircraft. It consists of a pair of trousers of inelastic light weight material beneath which bladders are inflated to apply counter pressure to the calves, thighs and abdomen. The bladders are inflated automatically from a high pressure source of air or oxygen via a valve which delivers a pressure of about 70 mb (1 lb/in^2) per *g* starting at $+2g_z$. Such a suit raises the black-out threshold of a relaxed subject by about 1·5*g*, but of probably greater value is the fact that it also reduces the amount of fatigue experienced by aircrew who are carrying out repeated manoeuvres involving high *g* levels.

Effects of $-g_z$ Acceleration

33. When the resultant of radial acceleration and gravity is directed towards the head as in a bunt, the body experiences footwards acceleration ($-g_z$). This axis of acceleration exposure is unpleasant and dangerous at much lower numerical values than when the inertial force acts from head to foot. Even simple inversion ($-1g_z$) causes engorgement of the head and neck due to the abnormally high venous pressure. When the level of $-g_z$ acceleration is increased the face becoms painfully congested, and the lower lids droop over the eyes so that sunlight shins through them and appears red—hence the term red-out. Unsupported blood vessels in the white of the eyes may rupture due to the high pressure and the resulting red discoloration takes several days to clear up—in common with bruising from any cause. Negative acceleration also has marked effects on the heart, the high blood pressures which develop at head level provoking a reflex which slows or even stops the heart for several seconds. In this way unconsciousness may be produced, the limit of tolerance being of the order of $-3g_z$ for 30 seconds, though $-5g_z$ may be tolerated for very brief (1-2 second) periods. As yet there is no practicable method of protection, although an inflated pressure helmet does offer a theoretical possibility. Fortunately, manoeuvres involving $-g_z$ are much less common than those involving $+g_z$, chiefly being confined to aerobatic display flying.