Injuries in Fatal Aircraft Accidents

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Mechanisms of Injury in Aircraft Accidents

The commonest cause of injury in aircraft accidents is the sudden deceleration that occurs when an aircraft hits the ground or water. However the forces acting upon the occupants are frequently less than those applied to the aircraft. This is because the aircraft structures absorb some energy as they collapse or are crushed. Modern design can aid the collapse of the aircraft so that it is controlled and the forces applied to the occupants are reduced. However lack of harness restraint may mean that the forces are magnified. The acceleration due to gravity is 9.81 ms^{-2} and is termed g. It is usual to refer to acceleration in terms of G, which is the acceleration applied to the individual divided by g. Therefore 10 G is 98.1 ms^{-2}. It is to be noted that deceleration is the layman's term for negative acceleration.

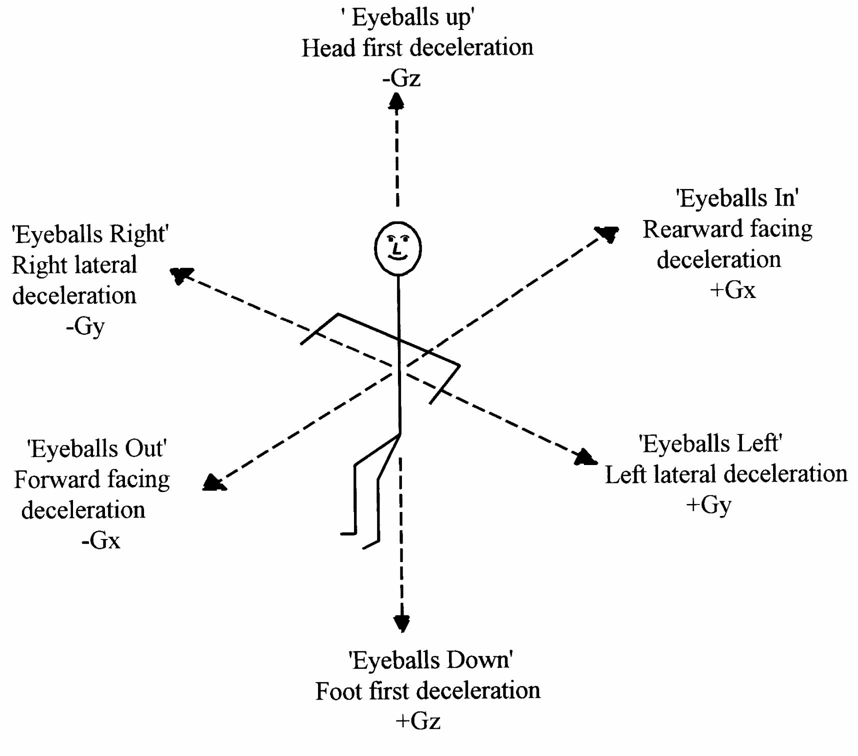

Figure 1. The effects of deceleration. The standard aeromedical terminology for describing the forces. The vector arrows indicate the direction of the resultant inertial forces.

Human tolerance to deceleration depends upon a number of factors including the duration, magnitude and direction of the inertial forces (Cugley and Glaister 1999). In most accidents the duration of application is short - less than 0.5 seconds. The direction of forces is a major determinant of tolerance. Man can tolerate Gx deceleration better than Gz, and Gz better than Gy. Personal variables such as

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gender, age, build and level of fitness also influence the ability of man to tolerate deceleration. Long bones are most susceptible to bending injuries while short bones can withstand stress but are most affected by crushing. Impact injuries cause the greatest damage to flat bones

Longitudinal forces occur during many crashes. They may be accompanied by collapse of the cockpit structure with injury to the occupant's legs leading to incapacity and failure to escape. It is believed that a negative acceleration or deceleration (-Gx, ‘eyeballs out’) of 45G may be sustained for a short period and 25G for longer without incapacitating injury (Anton 1988). Much higher forces can be tolerated if rearwards facing seats with high backs are provided. Decelerations over 80G (+Gx, ‘eyeballs in’) have been tolerated with this configuration. This is the rationale behind the drive to provide rearward facing seats in passenger carrying aircraft.

Vertical loads are also applied if the aircraft has a high sink rate. The occupants will tolerate these forces less well. Minor injuries, including compression of the vertebrae, can occur with +Gz decelerations of 25G. Abrupt vertical deceleration frequently results in break up of the floor structure to which the seats are mounted and failure of the seat mountings leading to serious injury. Heavy vertical (+Gz, eyeballs down) deceleration will produce the well-recognised ring fracture at the base of the skull due to force being transmitted through the spinal column. There is often additional disruption of the sacro-iliac joints and of the lumbar transverse processes; sometimes there is stripping of the mesentery and bowel from the posterior abdominal wall. The landing gear may be forced up through the floor injuring the occupants. It may also rupture fuel lines leading to the rapid onset of fire from which the occupants may be unable to escape because of their injuries. Fire occurs in 47 per cent of commercial aircraft accidents, 32 per cent of military accidents and 26 per cent of general aviation crashes. The engines of helicopters are often mounted above the cockpit and collapse of the aircraft may lead to these encroaching into the cockpit area and causing severe injury to the occupants. Deceleration in the opposite direction, -Gz, is unusual in aircraft accidents. However experimental evidence suggests that the restrained, seated subject is able to withstand 15G without serious injury.

Tolerance limits for lateral impacts, Gy deceleration, are not well defined, but is has been suggested that limits of 11 – 12 G are tolerable for an occupant restrained by a harness into the seat. Transverse loads occur when an aircraft hits the ground with moderate angle of bank. This often leads to break-up of the fuselage, exposing the occupants to injury by direct contact with jagged metal edges of the disrupted aircraft structure.

Injuries are caused by the interaction of the victim with the aircraft. In many crashes the aircraft structure collapses and the individual is injured by impact with the airframe. These injuries can include amputations, major lacerations and crushing. When the structure collapses, the victims may become trapped within the wreckage and die of fire, drowning or traumatic asphyxia. Harness restraint systems are provided in aircraft and these may modify the injuries that are sustained. The unrestrained head will swing forward when the torso is effectively restrained and the body is exposed to eyeball-out or -Gx acceleration. This may put a strain on the atlanto-occipital articulation, which is increased if a heavy helmet with, for example, night vision goggles attached is worn. This joint, therefore, needs careful evaluation. Pivoting over a lap strap often produces tears in the lower part of the small bowel mesentery and other bowel injury. The restraints themselves may fail. This may occur in the harness, its mountings, or the seat or floor may fail. When this happens the unrestrained victim can be injured by secondary impact against fixed structures.

Items of equipment within the cabin, which are not adequately secured, may break free in a crash and cause injury by secondary impact with the occupants. Overhead lockers are a particular source of loose items such as bottles that may cause significant injury. The heavier these items, the more likely are injuries. Flying debris from overhead lockers was a major cause of head injury in the Boeing 737 disaster at Kegworth in January 1989 (White *et al* 1993).

Pathologists involved in accident investigation have devised guides to enable them to determine the forces applied to a victim in an aircraft crash. These guides are derived from their experience of accidents where the forces are known and also from evidence obtained from laboratory studies. Table 1 gives an example of the decelerative forces needed to cause certain injuries.

Injury sustained	Deceleration
Nose - fracture	30G
Vertebral body - compression	20-30G
Fracture dislocation of C1 on C2	20-40G
Mandible - fracture	40G
Maxilla - fracture	50G
Aorta - intimal tear	50G
Aorta – transection	80-100G
Pelvis – fracture	100-200G
Vertebral body – transection	200-300G
Total body fragmentation	>350G

Table 1. Injury and deceleration needed

Post mortem artefacts may be seen, particularly in cases of burning, which occurs in approximately one third of all powered aircraft accidents. Fire causes the characteristic pugilistic attitude in the victim; this may be accompanied by fractures of the long bones and loss of the digits. The high temperatures may produce intracranial steam resulting in "blow out" fractures of the cranial vault simulating impact injury. The heat may also cause extravasation of blood into the extradural space simulating a haemorrhage. The blood in these cases often shows heat coagulation.

Another commonly encountered artefact results from part of the body being soaked in aviation fuel after or at the time of death. Skin slippage occurs which may be confused with second-degree burns.

Injury Analysis and Scoring Systems

Injury scoring as a means of classifying the extent of trauma has been used for many years. The Abbreviated Injury Scale (AIS) defines the threat to life in anatomical terms and has been accepted at a method of assessing the severity of trauma in road traffic accidents. However, the majority of victims die from more than one fatal injury and injuries which on their own may not be life threatening may be significant when combined with other injuries. An Injury Severity Score (ISS) was devised (Baker *et al.*1974) as a method of assessing victims with multiple injuries. This provides a useful predictor of mortality, survival time, length of hospital stay and disability (Bull 1975). Hill (1987) used a modified injury scoring system that has been found to be useful in assessing the injuries in aircraft accidents. The injuries sustained by the various anatomical regions are graded and the total for each victim is calculated.

Severity of Injury	Score	Force Needed	Potential Disability	Threat to Life
None	0	-	-	-
Mild	1	Little	None	None
Moderate	2	Moderate	Possible	None
Severe	3	Considerable	Probable	Possible
Fatal	4	Considerable	Fatal	Fatal

Table 2. Injury Scoring System (Hill 1987)

In practice, this system has proved sufficient for the purpose of assessing injury patterns in fatal aircraft accidents.

Some Specific Injuries

Head Injury

Head injury is very common in aviation accidents and was seen in two thirds of our cases. In most of these the head injury caused or contributed to the cause of the death. A significant finding was that the base alone was fractured in 18.9% of the fatalities that were not disintegrated. The base alone was fractured in 15.7% of military aircraft accident victims, 17.1% of helicopter fatalities and 20.4% of light aircraft accident deaths.

There are two mechanisms which cause this occult head injury. The first involves transmission of the impact forces through the mandible and temporo-mandibular joint to the base of the skull. This results in a transverse fracture that runs forward from the joint anterior and parallel to the petrous temporal bone. The two portions of this fracture join in or just posterior to the pituitary fossa. This is sometimes known as the "hinge fracture". There may be seemingly trivial external injury in these cases. These fractures may result in secondary shearing fractures of the vault.

The second common fracture of the base is a result of the forces being transmitted through the vertebral column and is found particularly with +Gz deceleration. These severe vertical forces are seen in falls from a height and when aircraft descend vertically in situations such as a stall. The result of these forces is a "ring" fracture of the posterior fossa. This occurs around the foramen magnum and may be a complete ring or, more commonly, an incomplete one. This fracture may communicate with the hinge fracture when the severe vertical forces also have a horizontal, -Gx component. In severe cases the forces may cause secondary "blow-out" fractures of the vault of the skull.

Spinal Injury

Spinal fractures are present in 45% of intact aircraft accident fatalities. There is no significant difference in the prevalence of spinal injury between the various categories of flying. A higher rate would be expected in rotary wing accidents because of the high incidence of accidents with a major vertical (+Gz) deceleration. However this was not seen and the rate was virtually identical to that seen overall. However when fractures of the spine were present, rotary and military accidents had a lower rate of multiple fractures – 58% in military accidents, 66% in rotary accidents as compared to 86% overall. In all categories of flying the thoracic spine was the most frequently fractured. This occurred in 29% of all cases.

In 10% of our cases there were fractures involving only the cervical spine. Many were fractures of the upper cervical vertebrae in extension giving rise to rupture of the anterior longitudinal ligament or fracture of the pedicles of the axis giving rise to the classic "hangman's fracture". Hyperflexion injuries were also seen; these cause rupture of the posterior ligaments and anterior dislocation of the superior vertebra. Crashes involving microlight aircraft, which may carry a passenger in tandem behind the pilot, may give rise to these injuries when the passenger rides forward over the pilot forcibly flexing the neck.

Pelvic fractures or disruptions are frequently seen and occur in some 49% of all accident victims. A ruptured bladder accompanies just less than one third of pelvic fractures.

Thoracic Injury

Injuries to the bones of the thorax are the most common injuries seen and occur in 80% of all accident victims. These injuries in turn cause trauma to the cardiovascular system. 47.6% of all accident victims had a ruptured heart and in 35% there was also a ruptured aorta. Only 10.5% had ruptured their aorta without rupturing their heart. Injury to the heart and aorta may arise in several ways. The most obvious is by direct penetration by the broken ends of ribs. However, the most frequent mechanism arises from compression of the heart between the sternum and spine.

In forward facing deceleration (-Gx) the chest is often compressed against fixed structures in the aircraft. Flexion injuries can also compress the chest as the chin falls forward and strikes the sternum – the so called "chin-sternum-heart syndrome", which was originally described in parachuting accidents (Simson 1971). Direct compression results usually in rupture of the atria and occasionally the ventricles. When the ventricles are lacerated this classically occurs in the right ventricle parallel to, and close to the left anterior descending coronary artery. When the rupture results from a sudden rise in intra-cardiac pressure, this may only cause endocardial laceration, typically, on the posterior wall of the atria.

Ruptured aorta is caused by the downward displacement of the heart by compression of the base of the heart between the sternum and the spine. It also arises when the deceleration is in the vertical (+Gz) direction and the heart continues to move down while the aorta is anchored. Ruptures usually occur just above the aortic valve ring or at the end of the thoracic arch just distal to the attachment of the ligamentum arteriosum.

Abdominal Injury

More than two thirds of the fatalities had abdominal injury. Rupture of the diaphragm was seen in 30.6% of unselected victims. This was slightly more frequent in the military aircraft accidents where 41.5% of the fatalities had a ruptured diaphragm. This presumably relates to the higher decelerative forces sustained in these accidents. The solid abdominal organs were frequently ruptured; 42.3% had ruptures of the liver and spleen while 18.4% had ruptures of the liver alone and only 4.6% had solitary ruptures of the spleen. The kidneys were ruptured in 23.5% of cases. Military accidents again showed a higher prevalence of these injuries; 56% of military fatalities had ruptured liver and spleen and only 12.9% had solitary ruptures of the liver with splenic rupture alone being seen in 4.7% of cases. Capsular lacerations of the liver suggest that these may be due to compression. However severe injury and internal disruption is common. In many cases the internal disruption of the liver is disproportionate when compared to the capsular damage suggesting that internal vibration or shearing may play a part.

Damage to the gastro-intestinal tract is, with one exception, uncommon. The stomach seems resistant to rupture except when it is herniated through a ruptured diaphragm. The intestines are similarly rarely lacerated. The one exception is that they are often bruised. The distribution of the bruising suggests that this is caused by compression of the gut between a lap belt and the spine. This mechanism may also be responsible for the fenestration of the mesentery that often accompanies the bruising of the gut serosa. The association of these injuries with the use of harness restraint is helpful in accident reconstruction as it demonstrates the use of seat belts. Cabin crew spend little time seated and for most of the flight they are standing in the cabin going about their business. When such seat belt injuries are seen in cabin crew it indicates that they were seated. If the accident occurred at a time during the flight when one would not normally expect them to be seated one may infer that the emergency was anticipated or that there was another reason, such as turbulence, for them to be seated.

Limb Injuries

Only 20% of fatalities from aviation accidents escape limb fracture, 73.6% having leg fractures and 56.6% having arm fractures. 64.5% of all fatalities had fractures of the lower leg and 52.6% had fractures of the femur. The arm was also frequently fractured; 42.5% had fractures of the upper arm and 42.3% had fractures of the forearm or wrist. These injuries mirror the forces that are applied to the limb and give some indication of the direction of that force. Inversion and eversion fractures of the ankle may be useful in determining the direction of force and, from that, some clues as to the attitude of the aircraft at impact. Fractures of the shin are seen when the legs flail forward and strike fixed structures or are trapped under the seat in front of the victim. Their value in accident construction and the assessment of safety equipment is discussed later.

Patterns of Injury and their role in Accident Reconstruction

The pattern of injuries sustained by the victims of aircraft accidents may give valuable clues that may aid the reconstruction of the sequence and circumstances of the accident. The "typical" passenger carrying aircraft crash is likely to result in either a uniformity of injuries or a steady logical gradation of injuries. Study of the injury patterns may allow the investigators to compare different accidents. This is particularly important when the circumstances of an accident are unknown such as when an aircraft crashes into the sea when there is no wreckage trail from which the impact attitude may be deduced and when little or no aircraft wreckage may be available for engineering investigation.

The Comet disasters of 1954 were the stimulus that prompted the formation of the RAF Department of Aviation Pathology. It was the study of the pattern of injury in the fatalities that pointed to the cause of these accidents (Armstrong *et al*. 1955). Similar studies of the patterns of injury in subsequent accidents have often indicated the attitude of the aircraft at impact or the nature of the impact itself.

Case 1

A Hercules C Mark I aircraft with six crew and 46 parachutists were carrying out a night exercise over the sea. The aircraft took off on a dark night with intermittent cloud. No calls were made and another aircraft on the same exercise saw it crash into the sea. A total of 32 bodies were recovered over the ensuing month. Divers recovered 30 of these from the aircraft or its immediate vicinity. They made a chart indicating where each body had been recovered. This chart was then correlated with the findings at autopsy. This chart is shown in Figure 2.

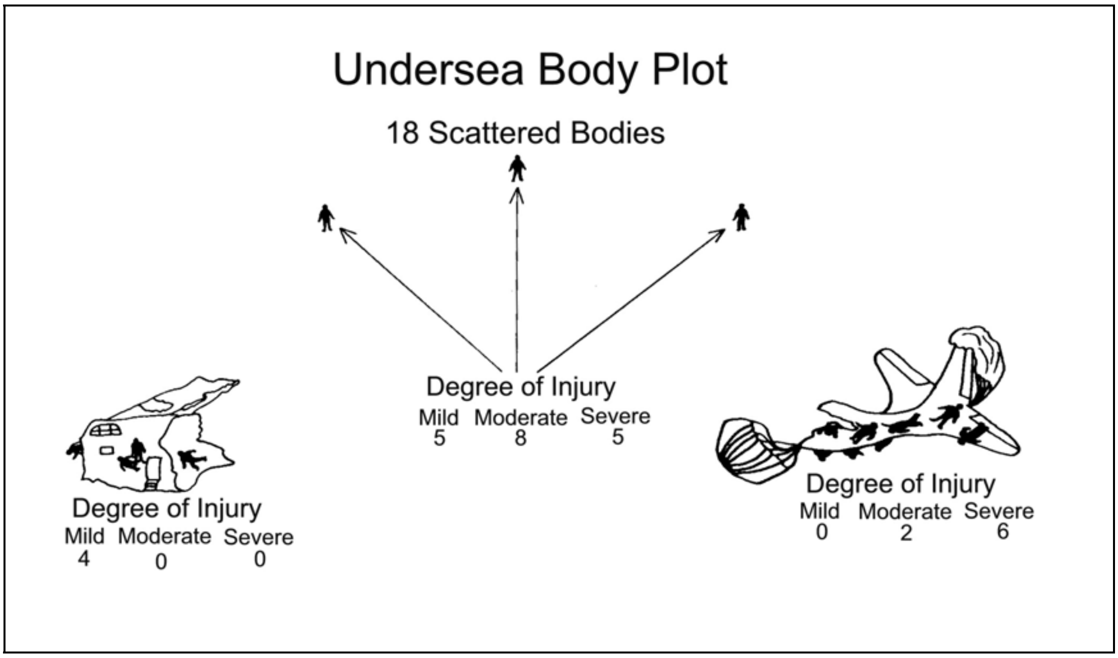

Figure 2. Plot relating injury to recovery position.

Analysis of the pattern of injuries (Cullen and Turk, 1980) suggested that those in the rear of the aircraft were more severely injured than those in the front. This suggested a tail down impact. The presence of limb flailing injuries suggested that the aircraft had made at least two impacts with the sea. The delay in recovering the bodies with the subsequent autolysis made histological examination impossible in all but a few of the bodies. However definite fat embolism was found in three bodies all of which had multiple immediately fatal injuries. This confirmed the hypothesis that there had been multiple impacts with the sea. The tail of the aircraft was recovered some time later. Examination of the damage confirmed that tail down attitude at impact.

Case 2

A Trident aircraft with 118 persons on board crashed shortly after taking off from Heathrow Airport with the loss of all lives. The autopsy findings revealed that all on board had severe injuries. Many had ruptures of the heart of the "paper bag" type. Many had hinge fracture of the base of the skull coupled with facial injury. Tables 3 to 5 show the injuries sustained by the victims.

Fatal Injuries	Number of victims
Ruptured Heart	86
Ruptured Aorta	21
Fracture of the Spine	73
Fracture of the Skull or Facial bones	80
Multiple Injuries (stated cause of death)	66

Table 3. Fatal Injuries sustained in Case 2

Leg Fractures	Number of victims
Femur only	14
Femur, tibia and fibula	45
Tibia and fibula	38
None	11

Table 4. Leg fractures in Case 2

Jack-knifing injuries	Number of victims
Chest only	12
Chest plus skull or facial bones	23
Chest and spine	16
Chest and head and spine	53
Head only	1
Head and spine	3
Spine only	1

Table 5. Jack-knifing injuries in Case 2

The injuries to the spine, the hinge fractures of the skull and the aortic ruptures all suggested a predominantly vertical deceleration. This view was supported by the fractures to the femur most of which occurred in the mid shaft and were thought to be caused by vertical impact between the femur and the front support of the seat. However only five passengers escaped chest injury and 23 escaped facial injury. The likely cause of these injuries was jack-knifing over the lap belt. Jack-knifing would also explain the ruptures to the heart and the mid-shaft fractures of the tibia and fibula. The conclusion derived from the pattern of injuries was that the aircraft had crashed with a predominantly vertical deceleration but that there was a significant horizontal element. This conclusion was supported by an examination of the crash site and the wreckage.

Case 3

The crash of the Boeing 737/400 aircraft on an English motorway near to the East Midlands airport was caused by an engine problem in the port engine leading to the pilot diverting to the airport. Due to confusion the starboard engine was shut down resulting in the crash only one kilometre from the runway threshold. The aircraft fuselage broke into three sections with the breaks occurring on either side of the wing.

An analysis of the injuries using the Abbreviated Injury Score (AIS) was used. The AIS was then used to derive the Injury Severity Score (ISS). The square root of the ISS was then used in the analyses to allow direct comparisons with other linear measurements of a similar scale (White *et al* 1993). The severity of the injuries mirrored the damage to the aircraft. While this is entirely to be expected these data may be used in the analysis of accidents where it is not possible to examine the crashed aeroplane, such as accidents over the sea.

The pattern of injuries in individual crashes may not be as clear-cut as that illustrated in Case 3. Two accidents over the sea serve to illustrate this point. Hill (1987) discusses the findings in another case. He found that the passengers towards the rear of the aircraft were more severely injured than those at the front. Subsequent investigation of the wreckage that was recovered confirmed the conclusion that the most severe damage to the aircraft was at the rear. The investigators believe that the aircraft crashed because of a mid-air break up following the explosion of an improvised explosive device. An earlier case further illustrates this point and also stresses the importance of injuries that do not fall into the general pattern of injuries – "the odd man out".

Case 4

This case has been well described (Mason and Tarlton 1969). A Comet aircraft disappeared over the Mediterranean Sea. Initially only bodies and flotsam were recovered. Post mortem examination of the victims revealed that some were severely injured while others had relatively slight injuries. The passengers were identified and as a seating plan was available, the injuries were compared with their seating position. It was noted that the more severely injured victims had been seated in the rear passenger compartment. One body was noted to show different injuries. The right arm showed a flailing injury and the skin of the chest showed minute wounds that were described as "peppering". The shirt also showed minute holes comparable to this peppering.

Radiological examination revealed numerous minute fragments within the chest and later X-Rays taken of the histology blocks revealed in one section of skin an opaque foreign body that was subsequently examined by a metallurgist and said to be typical of those that come from an explosive device. Among the flotsam was a cushion that also showed penetration by hot foreign objects. Similar foreign bodies were found in the cushion and by tracing the angles of entry it was possible to determine the origin of the fragments. It was determined that the aircraft had crashed because of the explosion of an improvised device that had been placed below the seat (Clancey 1968).

Case 5

This accident involved a piston-engined aircraft that crashed into a built up area while attempting to land at an airfield. The speed at impact was very low and the wreckage trail was short. A period of some ten minutes elapsed before the onset of a fire during which time many of the passengers were seen to be alive and conscious within the cabin. The hull of the aircraft remained substantially intact. Despite this 70 of the 81 passengers on board died. Of the fatalities 35 had died of burning. The majority of these had impact injuries to their shins resulting in fractures that inevitably would have prevented their escaping the ensuing fire (Mason 1970). While some victims did have head injuries caused by flailing over the lap belts and striking the seat in front, the majority did not. Examination of the passenger seats revealed that the thin bar situated at the base of the seat back was deformed. The mechanism for the fractures to the lower legs was thought to be flailing upwards against the bar at the rear of the seat in front of the victim. A direct result of the investigation of this accident was the modification to seat design in attempt to prevent recurrence of these life-threatening injuries.

Leg injuries occurred in 70% of the victims of this accident. A later accident occurred in similar circumstances with the aircraft "undershooting" the airfield. Following the improvements in seat design only 10% had similar lower leg injuries. However 23% had head injury due to flailing over a lap belt.

Patterns of Injury in Comparative Accident Investigation

Having a centralised department investigating all fatal aircraft accidents facilitates comparative investigation. Careful analysis of the injury patterns when the circumstances are known may aid accident reconstruction when the circumstances are unknown. Case 6 was a moderately high-speed crash over land with the passengers restrained by lap belts while Case 7 was an accident over water in which the nature of the impact was unknown. Unfortunately only very few bodies were recovered. Comparison of the injuries sustained by the victims is shown in Table 6. It can be seen that the similarity of injury pattern in these cases is striking. It was concluded that the accident over the sea was a similar impact at moderately high speed with the passengers restrained by their lap belts.

Injury	Case 6 Over Land 46 victims	Case 7 Over Sea 10 Victims
Head Injury	42	10
Lower Leg Injuries	45	10
Combined Head/Leg Injuries	41	10
Lap Belt Injuries	17/20	6/10

Table 6. Comparison of injuries sustained in two accidents

Further comparison can be made between accidents over the sea (Mason 1973). If Case 7 is compared to Case 4, discussed above, the differences are marked (Table 7).

Feature	Case 7	Case 4
Salvage Rate	23%	77%
Salvage Pattern	Fanning	Scattered
Injury Pattern	Uniform	Clear Cut Groups
Head Injury	Mainly Maxillary	Mainly Parietal
Lap Belt Injury	Almost Constant	None
Lower Leg Injuries	Constant	Absent
Clothing on Bodies	Present	Lost in 30%

Table 7. Two clearly dissimilar accidents over the sea

Happily improvements in flight safety have ensured that major accidents are less common and for this reason the examples given are from the earlier work of the department.

Recurring Injury Patterns

In the early 1970s the frequency of certain injuries in light aircraft was apparent (Cullen 1973). The regularity of low speed light aircraft crashes was such as to suggest that our efforts would best be directed at injury prevention. A problem was encountered in that no attempts had been made in previous analyses to distinguish between survivable accidents and those that were clearly not survivable. The injury patterns in the non-survivable accidents would clearly confound any analysis. A survivable accident was defined as one in which a survivor resulted or that the deformation of the casualty's immediate environment was so minor that survival would have been likely had adequate equipment been provided. The frequency of head injury above the eyes was surprisingly uncommon, occurring in only one third of cases. More than 75% had died of cerebral trauma involving the middle third of the face. This sort of injury is clearly not amenable to protection with a helmet.

Often these injuries resulted in fatal fractures to the skull but in some involving the middle third of the face death resulted from complications of the injury such as inhalation of blood. These injuries may also incapacitate the pilot preventing escape from the post crash fire. The discovery of these injuries together with evidence of flailing such as hair and tissue embedded in the instrument panel is evidence that death should be prevented by the provision of upper torso restraint.

Other injuries caused by flailing include rupture of the heart due to the “chin-sternum-heart” syndrome. At the time of this study only half of the pilots of light aircraft were provided with shoulder harness. The injuries were analysed to see if there was a significant difference in the injuries sustained when those provided with a shoulder harness were compared with those having a harness consisting of only a lap strap. To my surprise there was little difference in the prevalence of flailing injuries. However, when the shoulder harnesses were examined it was clear that the harnesses involved were frequently of a poor design and this had led to failure of the harness. In 76% of the fatalities provided with a shoulder harness the harness had failed or been unfastened.

These findings suggested that the fatality rate could be drastically reduced by the incorporation of efficient upper torso restraint particularly if this was coupled with the use of adequate head protection. Most light aircraft used in the United Kingdom are manufactured in the United States. As long ago as 1966 a Federal Aviation Agency Report (Young 1966) stressed that the use of inadequate or incomplete body restraint was a major factor in the trend of increasing numbers of fatal injuries reported from general aviation accidents. Pressure from accident investigators in the United States and the United Kingdom brought about amendments in 1973 to the Federal Aviation Administration regulations requiring the provision of shoulder harness for flight crew positions and also requiring that they be kept fastened while flying.

Who was at the Controls at the time of the Crash?

Many aircraft fly with two pilots. In determining the cause of an accident it is important to know which pilot was in control of the aircraft at the time of the crash. The provision of cockpit voice recorders in commercial aircraft may help this task. When incapacitation is suspected in a single pilot aircraft it is crucial to know if he was controlling the aircraft at the time of the crash. Only one pilot is in charge of the controls at any one time while the other pilot concerns himself with observation of instruments and the airspace close to the aircraft. The second pilot may also be involved in cross checking navigation. Either the pupil or instructor may be in control of training aircraft. Modern long-range aircraft are fitted with an automatic pilot. When this is engaged the pilot may even leave his seat in the cockpit to perform other tasks. However it is usual for one pilot to be in his seat at all times.

The design of the controls, the pilot’s position and the manner of operation of the control system must all be known before one can determine which pilot was in control at the time of the accident. The design of control assemblies, rudder pedals and other control levers varies from aircraft to aircraft. Fixed wing aircraft frequently have a horn assembly as a control; this may be U-shaped or similar to a car steering wheel with spokes. Military aircraft frequently have a control stick contoured to fit the pilot’s right hand. This stick may incorporate switches for operation by the right thumb or fingers. Rudder pedals also differ in their construction.

The activities of the pilot during flight are not confined to the operation of control column and rudders pedals. He must handle a variety of different controls on or above the instrument panel, in the roof, on the consoles or at his side on the floor. These controls include the engine throttles, brakes, landing gear, etc. There are many switches and toggles that must be used in flight and there are many instruments that must be monitored.

Helicopters are equipped with different controls. They have a control stick and rudders that must be used during flight. Vertical movements are controlled with a special pitch lever that is situated to the side of the pilot and usually operated with his left hand. With this he can control the speed and pitch of the main rotor blades. The pitch of the tail rotor is controlled with foot pedals.

The pilot's position

When flying the aircraft, the pilot's arms form a forward right angle with one hand operating the control column and the other operating the throttles or other switches. The control column may be operated with either hand or both. The pilot's feet rest on the rudder pedals during manoeuvres such as take-off and landing. They are bent upwards at an angle of about 45^{o} in normal operation but they may be removed in level flight. The precise position of the hands and feet depends on the layout of the cockpit. If, for any reason, the pilot becomes unconscious he is unable to maintain this position. His upper torso will tilt forward until it is restrained by the shoulder harness and his chin rests on his chest. The hands fall off the control column and come to rest on his lap or by his side with the palmar surfaces facing forward.

The mechanism of injury

The abrupt deceleration when an aircraft crashes propels the pilot's body in the direction of flight. Damage may occur in the hands and feet if they are on the controls at the moment of impact (Krefft 1970). The injuries that are sustained may mirror the shape of the controls involved and depend on the direction and magnitude of the forces that are applied. The area between the thumb and index finger is particularly likely to be injured if the control column is being grasped at the moment of impact. Patterns and abrasions may be seen which mirror the grips or switches on the control column. These injuries are seen on the palmar surface of the hand. In severe accidents the thumb may be severed. The injury caused by flailing of a hand that is manipulating the throttle is, in contrast, seen on the dorsal aspect between the wrist and the knuckles.

The force directed between the thumb and index finger during control column injury may be transmitted to the wrist and forearm. This may cause fracture or dislocation of the wrist. The stress applied to the forearm may cause fractures of the arm. These are frequently found in the lower third and are usually in flexion; the distal fracture ends commonly penetrate the extensor surface of the arm. If the forces are applied to the elbow, posterior fracture dislocation may be seen. The control column frequently breaks and, in these circumstances, lacerations will occur on the palmar surfaces of the hands; fragments of the control column may occasionally be found in these injuries.

When the pilot's feet are resting on the rudder pedals at the moment of impact they are subjected to excessive force on the soles corresponding to the area of the pedals. The construction of the rudder pedals will determine the nature of the foot injuries; bar shaped bruises and transverse fractures of the tarsal bones being often seen. Because of the angle of the feet on the pedals, the heel is subject to strain and comminuted fractures of the tarsus may occur. The injuries sustained in the feet that are caused by the rudder pedals are found on the plantar surface; those due to flailing are seen on the extensor surface of the feet and lower legs.

Injuries due to controls will only be sustained when there is sufficient force. If such a force is present, the absence of these injuries may indicate that the pilot did not have his hands and feet on the controls at the moment of impact. It is important to note that persons other than the pilot may sustain similar injuries if their hands and feet adopt similar position to those of the pilot; feet resting on the bar of the seat in front will sustain injuries indistinguishable from those caused by pedals. Hence it is important that these injuries are interpreted in the light of all the evidence that is available.

The forces applied to the pilot may also cause injuries to the head and trunk. The head may strike parts of the instrument panel leaving imprints on the forehead or face. Patterns derived from the configuration of knobs and switches on the panel may be seen. Occasionally instruments may be embedded in the skull or face. Fragments of glass from the face of dials may be found in the wounds that arise from contact with the control panel. Blood or hair that is found on the control panel might mirror the wounds on the pilot's head.

Witness marks from lap strap and diagonal harness may indicate which seat the individual was occupying. If a shoulder harness in not worn, or if it fails, the upper part of the body will flex forward and frequently strikes the control column, causing characteristic wound to the anterior chest.

Injuries that are due to the manipulation of controls and pedals are found on the palmar surfaces of the hands and the plantar surfaces of the feet. Contact injuries caused by the limbs flailing and striking specific instruments or levers within the cockpit are almost always found on the extensor surfaces of the hand or lower limbs.

Examination of clothing

Pilots wear gloves and boots. Because any protective clothing always absorbs the force of the impact, gloves and boots may show damage from control levers and switches at the time of the accident. Detailed examination of the pilot's clothing is an essential part of the post-mortem examination. Ideally the bodies will remain clothed so that the examination of clothing may be conducted 'in situ'. Tears and impressions may be discovered on the gloves and boots that reflect the contours of the controls that inflict them. Equally pieces of clothing and, occasionally, blood or tissue from the pilot may be found on the switches and controls that caused the injuries. Post-mortem analysis using serology or DNA typing may be needed in situations when it is vital to know the origin of such blood or tissue.

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