L5-208

AVIATION PATHOLOGY

Steven C. Cogswell, MD
LtCol, USAF, MC, FS
Deputy Armed Forces Medical Examiner

INTRODUCTION

Aircraft crashes are generally predictable in type and frequency. Different types of aircraft have different types of crashes. Similarly, occupant injuries follow generally predictable patterns, and themselves often consist of patterned abrasions and contusions reflecting portions of the aircraft structure. The role of the medical investigator and/or pathologist includes documentation and interpretation of these injuries to determine how the injuries occurred so that they may be minimised or prevented. The pathologist's documentation and interpretation of injuries, together with manifestations of natural disease processes, provides the core of the Human Factors data for analysis. As few pathologists are familiar with aircraft crash injuries, their interpretation of the injury patterns may be incorrect, which may significantly compromise the investigation.

Although the general aviation accident rate has steadily declined, the fatality rate remains high. A fatal outcome is twice as likely as a serious injury, in contrast to automobile crashes, wherein there is a tenfold greater incidence of serious injury over death. In commercial (passenger) aviation, the problem of escape from the crashed aircraft remains high. An accident involving in-flight breakup or a high-angle, high-speed impact into ground is clearly non-survivable. But such crashes are uncommon. The majority of airline crashes occur during the take-off and landing phases of flight. Speed is relatively low, and impact angles shallow. The decelerative forces on the passengers are, therefore, often survivable. It is unfortunately common for the passengers to survive the impact, but die in the post-crash fire.

PATTERNS OF INJURY

Different types of aircraft have different flight operations, and, therefore, tend to crash in different, generally predictable ways. Their occupants will tend to have similar patterns of injury. The general concepts of crash worthiness have been most extensively incorporated in the design and construction of aerial applicator aircraft built since the early 1960's. These crash safety design features include: Aft location of the cockpit to provide maximum crushable space and allow for rearward displacement of the engine without intrusion into the cockpit, design of the cockpit as the strongest part of the airplane, incorporating a keel beneath the fuselage to allow the airplane to slide along the ground, placing fuel tanks away from the cockpit and engine to reduce the possibility of fire, and incorporating strong seat belt and restraint systems.

Light Aircraft

These airplanes comprise the vast majority of the general aviation fleet. Most light airplanes weigh between 900 and 2000 kg, although they may weigh as much as 5500 kg. Typically they are powered by one or more reciprocating engines. Most accommodate two to six people. Usually they are equipped with two sets of flight controls. Take-off and landing speeds are approximately 100 - 150 km/h. Most cruise between 150 and 300 km/h.

The majority of accidents occur during take-off and landing at relatively low speed. Fatal injuries are often qualitatively similar to those seen in high speed automobile accidents. Angles of ground impact are commonly shallow, so that the aircraft may bounce or slide along the ground, reducing peak decelerative loads.

During the crash sequence the victims are seated and wearing either lap belts or lap belt-shoulder harness combinations. Injuries of head, neck, and upper torso are related to the degree of upper torso flailing and structural deformation of the passenger compartment. Flailing injuries of extremities are common. Legs may be injured by upward collapse of the passenger compartment floor.

Occasionally a light airplane experiences a major structural failure in flight, or a mid-air collision. Crash forces in such accidents may approximate those which occur on ground impact from free-fall (approximately 36 m/s).

Aviation fuel is readily volatilized during a crash, and there are many possible ignition sources; post-crash fires are common. Thermal damage complicates victim identification and assessment of mechanical injuries. The pathologist must differentiate pre-mortem from post-mortem burns and determine the relative importance of thermal-toxic versus mechanical injuries. The possibility of in-flight fire with incapacitation having occurred prior to ground impact must also be considered.

Rotary Wing Aircraft (Helicopters)

Most helicopters have a single rotor with two

Paper presented at the AGARD AMP Lecture Series on "Injury Prevention in Aircraft Crashes: Investigative Techniques and Applications", held in Farnborough, UK, 24-25 November 1997, and Madrid, Spain, 1-2 December 1997, and published in LS-208.

or more blades. Some of the larger or special purpose helicopters have two separate rotors. Power is provided by one or two engines which maybe of either reciprocating or turbine type. Forward cruising speeds are generally between 130 to 300 km/h.

Safety design considerations are complicated by the necessity of positioning the large and rapidly revolving rotor blades over the fuselage, and the need for locating heavy engines, gear boxes, fuel tanks, and occupants near the center of gravity beneath the gyroscope-like rotor. Weight limitations restrict the degree of structural stiffening of occupant areas. The need for unobstructed forward and downward vision places the pilot(s) in the nose of the aircraft where little aircraft structure is available to absorb crash forces. Helicopter crash forces are primarily in the vertical axis.

There are few injuries sufficiently distinctive to be called characteristic of a helicopter accident as opposed a fixed-wing aircraft mishap. An unbalanced rotor, usually the result of a blade striking trees or the ground and losing the tip, will cause the rotor blades to flail wildly. The rotor blades will often strike the fuselage and cockpit, and may sever the tail boom, disrupt fuel cells, and/or cause decapitation, amputations, or transections of the occupants, something rarely seen in fixed-wing aircraft crashes. Multiple fatal injuries are primarily caused by vertical crash forces, collapse of cabin structure, and crushing beneath engines and gear boxes. Head injuries are especially common among pilots, due to their exposed forward location. Protective helmets considerably reduce the likelihood of head injury. They are routinely used by military aviators, but seldom by civilians.

Fire is of special concern in helicopter crashes. The fuel cells cannot be located any great distance from the occupants, and are usually directly beneath or behind the cabin. Many victims survive the crash only to die in the subsequent fire. The U.S. Army developed a crashworthy fuel system to prevent these deaths.

Crashworthy helicopter design is typified by the U.S. Army UH-60 Blackhawk. Attenuation of crash forces is provided by the landing gear (designed to absorb approximately 15 G) and the vertically-stroking seats, which absorb approximately 30 G. Stroking of the seats also moves the pilots down and away from the windscreen. A crashworthy fuel system will prevent fuel spillage and fire up to approximately 80 G. The entire design is such that the usual 50 G limit of survivable crash forces has been pushed to approximately 80 G (in the vertical axis), and post-crash fire will not be a factor until crash forces have exceeded the limit of survivability.

Air Transport Aircraft

A wide range of aircraft types are used in transport operations. Small "airliners" are similar to the larger general aviation aircraft. At the other extreme are the wide-bodied airbuses used in intercontinental service. The "typical" modern airliner is powered by two, three, or four turbine engines. It carries from a few people (as on training flights) to several hundred. Take-off and landing speeds are on the order of 250 km/h. Commonly these aircraft cruise at 900 km/h, at altitudes up to 12 km.

Accidents with ground impact at high speed result in disintegration of the aircraft and its occupants. Intermingled aircraft and human remains may be scattered over thousands of square meters. Fortunately, such crashes are uncommon. Crashes during take-off or landing are much more common. Typical of such crashes, speeds are relatively low and impact angles shallow. Deceleration time is prolonged, and peak G-loading is reduced. Energy is dissipated as the aircraft slides along the ground and its structural components are deformed by crash forces. The fuselage may remain relatively intact.

About one-half of the fatalities which occur in air transport accidents are not the result of impact injuries. Rather, they result from thermal-toxic injuries during the post-crash fire. To escape from the wreckage, passengers and crew must successfully reach, open, and pass through doors, emergency exits, or rents in the fuselage. As many as three-quarters of the exits are not used because of jamming, blockage, fire, smoke, or other factors.

Injuries sustained during the decelerative phase of a crash, such as legs broken by flailing against seats, head injures from impact against seats and tray tables, or perineal and buttocks injures associated with downward failure of seats, may have incapacitated the victims. Correlation of injury patterns with crash dynamics and structures in the vicinity of each victim is essential to understanding the mechanisms of injury.

It should be noted that, while considerable attention has been given to improving crash survival and occupant escape in military fighter-type aircraft and helicopters, and recently to improving crash safety standards for automobiles and other ground vehicles, rather little work has been directed toward providing similar protection for air transport passengers and crews.

Fire may envelop a crashed airliner in a matter of a few seconds, or it may take several minutes. The cylindrical fuselage may act as a flue or chimney drawing fire through the passenger compartment with gale-force winds. In addition to large quantities of smoke and carbon monoxide, a wide variety of other combustion products are liberated from burning fuel, lubricants, hydraulic fluid, and the plastic materials used in aircraft interiors. Among these combustion products are HCN, NOx, HF, and HCl. The toxicology of these various combustion products, and their effects in combination with the inevitably present carbon monoxide, are the subject of ongoing research.

Fighter-Type Aircraft

These high performance airplanes carry either one or two aviators. Two-place aircraft may have side-by side or tandem seating and two sets of flight controls. Take-off and landing speeds of 250-275 km/h are common. Cruising speeds are generally in the range of 900-1000 km/h. Many of these aircraft types are capable of sustained supersonic flight. Operating altitudes in excess of 12 km. are not unusual. However, some fighter-type aircraft are also routinely flown at high speed and low altitude, as on gunnery ranges or terrain-following missions.

When a modern fighter aircraft crashes it usually disintegrates. High speeds and/or high angles of ground impact produce crash scenes aptly described as "smoking holes". If the victim remains in the aircraft at ground impact the body is likely to be fragmented. Specific kinds of missions of specific types of aircraft are also associated with an increased incidence of accidents, e.g. low-level bombing runs at night, ground-attack, etc. Fighter aircraft are frequently operated near the limits of human physiologic and psychomotor capability. Similarly, the aircraft are sometimes operated near the limits of their aerodynamic and structural capability. The Aircraft Accident Investigation Board has access to the accident history of the aircraft type involved in each crash. This well-documented "epidemiology" of military aircraft accidents is extremely useful to the crash investigators because it alerts them to common "failure modes" of both the machine and its human operators.

Fighter aircraft are equipped with ejection seats, designed to propel the seat and its occupant clear of the aircraft, release the restraining harnesses, separate the occupant from the seat, and initiate parachute opening. Typical vertical velocity during ejection is 15-20 m/s, with peak velocity being achieved in about 1.25 meters. The aviator is subjected to an 18-20 G. acceleration. Elapsed time from initiation of ejection to parachute opening is about one second. During bail-out at high altitude parachute opening is automatically delayed, and the aviator free-falls to lower altitude (about 4500 meters) before an aneroid device deploys the parachute.

Modern ejection systems have an excellent record of reliability when used within the so-called "ejection envelope"; that is, within the limits of altitude, airspeed, aircraft attitude, and sink-rate for which the system was designed. Most fatalities occur because the ejection system is activated so late in the accident sequence that effective parachute opening cannot be achieved prior to the victim striking the ground. Thus, if in-flight escape was attempted but unsuccessful the victim's body tends to be relatively intact. Injury patterns reflect lethal events which occurred during or subsequent to ejection. Occasionally ejection is successfully accomplished and parachute opening achieved, but the aviator is killed by landing in electric power lines, drowning, being dragged across the ground by high winds, or descending into the flaming wreckage of his own aircraft.

Aviators who operate high performance military aircraft wear life support equipment including protective helmets, oxygen masks, parachutes, and G-suits. Malfunction of any of this equipment may be a cause factor in an accident, or may preclude successful in-flight escape from an impending crash. Thus, it is essential that the Medical Investigator/Pathologist have the expert assistance of a military Flight Surgeon and/or Aviation Physiologist who is often able to recover and assess the functional state of key life support components.

A note of caution is warranted. Military aircraft sometimes crash with live ordnance, such as bombs and rockets aboard. Unfired ejection seats contain ballistic and rocket charges which may remain capable of causing serious injury or death should they be inadvertently activated. The military services provide ordnance specialists who will disarm these devices. Personnel not essential to rescue and fire-fighting operations should not approach aircraft wreckage until it has been declared "safe" by the Fire Marshall and/or the ordnance specialists.

GENERAL CONSIDERATIONS

As in the investigations of other modes of violent death, autopsies of aviation accident victims are usually performed while only incomplete and sometimes inaccurate information is available from the death scene. Consequently, free exchange of information between pathologist and crash-site investigator is essential. Premature conclusions based solely on autopsy findings must be avoided.

The pathologist should familiarize himself with the general features of the aircraft involved, the nature of the accident, and the specific interpretative problems likely to be encountered. A tour of the crash site, in company with the Flight Safety Investigator or Flight Surgeon, is especially helpful. An appreciation of the physical setting and some concept of crash dynamics greatly assists in the interpretation of injury patterns. The investigating Flight Surgeon should attend the autopsy.

The pathologist is seldom able to make an initial examination of aircraft crash victims while they are still in the wreckage. Usually the bodies will have been removed by rescue or fire fighting personnel. Frequently the locations of victims within the aircraft will not have been recorded. Since interpretation of the postmortem examination depends on detailed knowledge of each victim's immediate surroundings and possible role in aircraft operation, this type of scene disturbance, innocently motivated, can jeopardize the entire Human Factors investigation. Therefore, the pathologist's first task is to establish the seating position location of each victim within the cabin/cockpit. Sometimes photographs will have been taken of the victims in the wreckage. Often it will be necessary to identify and interview the people who moved the bodies.

The pathologist is dependent on highly specialized technical assistance to interpret his observations. Injury patterns not understood at the time of autopsy may have critical significance when related to specific aircraft structures and crash dynamics. Similarly, the hardware/operations investigators and Flight Surgeon must base many of their conclusions on autopsy and toxicological findings. Documentation of observations made during autopsy is of extreme importance. The Pathologist's primary responsibility is to observe and to document. Final interpretation must be a collaborative effort between the pathologist and the other Human Factors investigators within the framework of the entire accident investigation.

COMMENTS ON DOCUMENTATION

Autopsy findings are eventually reduced to a written narrative, with accompanying anatomic drawings or diagrams, which constitutes the work product of the pathologist. These materials become part of the accident report prepared by the Flight Safety Investigator or the military Aircraft Accident investigation Board. Photographs and roentgenograms of crash victims are not ordinarily forwarded as part of the official record, but rather are retained in the files of the medical investigator/pathologist. Photography and roentgenography not only provides additional means of documentation, but, when properly used, are powerful investigation tools.

Photographs

Photographic documentation begins at the crash site. The primary investigators take numerous photographs of the aircraft wreckage and surrounding terrain. These photographs depict damage to aircraft structures but only incidentally show the injuries to aircraft occupants or body positions. The pathologist should, therefore, be prepared to take his own photographs of the crash scene. Emphasis should be placed on the cockpit/cabin area of the aircraft and the locations at which bodies were recovered. Ideally, this photographic record begins before the bodies of the victims are removed. Crash sites, especially those of general aviation accidents, are seldom secure. Wreckage is soon disturbed and the value of scene information rapidly degraded.

Photographs of crash victims, clothed and then unclothed, with special attention directed toward external manifestations of injuries, even those injuries which appear inconsequential, should be taken under the good lighting conditions of the morgue. Internal injuries and significant natural disease processes should be photographed. Thorough photographic documentation of broken hardware and human injuries greatly facilitates retrospective analysis of crash injury patterns.

Roentgenograms

Roentgenographic examination of crash victims can provide significant information which is difficult or impossible to obtain by other means. Roentgenograms can be used to establish positive identification of crash victims when fingerprint or dental comparison are not feasible. Anatomic sites, such as maxillary and frontal sinuses which are important in aviation physiology but seldom examined at autopsy, are readily visualized. Radio-opaque foreign objects imbedded in bodies, such as bits of flight instruments or bomb fragments, are readily demonstrated. "Control injuries", those blunt force injuries of hands and feet that indicate the aviator was attempting to control the aircraft at impact, are more easily demonstrated roentgenographically than by autopsy, as are the vertebral compression fractures associated with high vertical loads.

TOXICOLOGY IN AVIATION ACCIDENTS

Toxicologic analysis of body fluids and tissues of persons fatally injured in aviation accidents is an essential part of the Human Factor investigation. Collection of appropriate specimens is part of the autopsy. Chemical agents of primary concern are ethanol, carbon monoxide, prescription and over-the - counter medications, and illicit drugs.

Ethanol

The intact body without decomposition presents no problems in ethanol level interpretation, assuming proper specimen collection and handling. Many aircraft accident victims are fragmented, with variable amounts of decomposition. In decomposing bodies, postmortem bacterial production of alcohols will artifactually raise the ethanol, although rarely above 0.05g/dL. Bacterial ethanol production is accompanied by other alcohols and congeners such as n-propanol and n-butanol; presence of these compounds indicates postmortem artifact, rather than ingestion. The ideal specimen is vitreous humor. It is protected from all but severe trauma, and decomposes slowly. Urine has similar qualities; blood is usually easily gotten, but decomposes quickly.

Carbon Monoxide

The toxicity of carbon monoxide increases as the partial pressure of oxygen decreases at higher altitudes. Thus, postmortem blood levels of carbon monoxide which might be of little significance at sea level produce significant pilot incapacitation at altitude. An elevated blood carbon monoxide level and soot in the airways may result from an in-flight fire or inhalation of combustion products in a post-crash fire. Carbon monoxide levels in occupants alive in fires occurring in small cabins (generally fewer than 10 passengers), or those exposed to a "fireball" of fuel will often be quite low. Rather than the 50 - 70% carboxyhemoglobin saturation typically seen in house fire victims, saturations are often 10 - 20%, scarcely above the baseline level for a heavy cigarette smoker. These deaths are probably due more to oxygen depletion and carbon dioxide production than to carbon monoxide. Thus, interpretation of postmortem carbon monoxide levels requires detailed knowledge of the crash sequence and the other autopsy findings.

Drugs

Toxicology examination of pilots (and other aircrew members) should include a "drug screen" and quantitation of any drug(s) detected. A pharmacological agent may be present in sufficient concentration to be incapacitating and, therefore, a "cause factor" in an accident. The presence of therapeutic levels of certain drugs may provide clues to symptomatic natural disease. For example, an antihistamine would suggest the possibility of an upper respiratory tract infection which might predispose to acute barotitis media or barosinusitis, the attendant pain of either being capable of causing distraction or partial incapacitation during a critical phase of flight.

Detection of quinidine would suggest a history of heart disease not documented in the victim's medical records. Similarly, finding one or more of the various tranquilizers would prompt further inquiry into the aviator's psychological and psychiatric history.

The victim's personal effects should be searched for medication containers, and in instances where prescription drugs are discovered the prescribing physician should be contacted in an effort to develop further medical history.

NATURAL DISEASE IN AVIATION ACCIDENTS

Occasionally aviators conceal manifestations of serous chronic illness, such as angina pectoris, diabetes mellitus, idiopathic epilepsy, or malignancy form their physician. Others choose to fly while suffering from acute conditions, such as respiratory tract infections, gastroenteritis, or migraine headache. Sudden collapse and/or death may result from acute coronary arterial insufficiency, ischemic or hemorrhagic cerebral infarcts, ruptured intracranial aneurysms, or spontaneous pneumothorax. Incapacities ranging from mild physiological disturbance to sudden death have been clearly established as the cause of specific accidents.

At autopsy, pilots manifest the same range of natural diseases as their passengers or any other group of reasonably healthy adults who die violent deaths. The incidence of atherosclerotic cardiovascular disease in military aviation mishap autopsies is approximately 15%. The mere presence of pre- existing disease does not mean that it was a factor in causing the accident. To avoid serious error, autopsy findings must not be interpreted out of context. For example, severe coronary arterial atherosclerosis and a healing myocardial infarct in a pilot might mean that a crash occurred because of in-flight incapacitation and/or death of the aircraft operator. The interpretation is quite different, however, if the engineering analysis of the aircraft wreckage, corroborated by the flight data records, indicates that the aircraft, while in straight and level flight, sustained a major structural failure due to a design deficiency and metal fatigue. A brain tumor might have initiated a grand mal seizure causing complete incapacitation of the pilot, loss of control, and crash. The tumor might be an incidental finding if that pilot could not have been in control of the aircraft at any time in the crash sequence.

OBJECTIVES OF THE AUTOPSY

The objective of the autopsy examination of aircraft crash victims can be summarized as a series of questions:

1. Who died?
2. What was the "cause of death"?
3. What was the manner of death?
4. What specific interactions between victim and aircraft structures/components resulted in injures?
5. If the Aircraft had provisions for in-flight escape, why did the victim(s) fail to escape?
6. If the victim(s) survived the decelerative forces of the crash, why did they fail to escape from the lethal post-crash environment?
7. What role, if any, did the victim(s) play in causing the crash?
   - A. Who was flying the aircraft?
   - B. Was the pilot incapacitated?
   - C. Were physiological aberrations initiating or contributory cause factors in the accident?

The injuries seen at autopsy are most conveniently and usefully separated by the location of injury (head/neck, abdomen, extremity, etc.) and the mechanism of each injury. Injury mechanism may be separated into the categories of **Decelerative, Impact, Intrusive,** and **Thermal.**

Traumatic Injuries

Head Injuries. In aircraft accidents, the head and neck region is especially susceptible to injury. Head injuries alone comprise the most frequent cause of death in aircraft accidents. Death often results from the head striking the instrument panel. Preventive measures, such as helmets and shoulder restraint systems, have reduced head injuries. However, the head can still strike the instrument panel, even with an effective torso restraint system in place, as a result of buckling of the fuselage. Also, since the crash impact can have enough energy to separate the helmet from the head, injury may follow. A fatal head injury can be sustained even if the helmet remains in place and intact. In this case, the helmet may have distributed impact forces widely over the head, leaving the scalp and skull undamaged while fatal forces were transmitted to the brain.

Severe impact forces can cause comminuted ("eggshell") fractures of the skull, or partial to complete decapitation. However, skull fractures can be subtle and require close examination at autopsy to be detected. The dura must always be removed and the skull base examined for hidden fractures. Force from an impact to the chin may be transmitted through the arch of the jaw to the temporomandibular joints, causing a basilar skull fracture through the middle cranial fossae. Forces transmitted up the spine in $+G_z$ impacts can cause ring fractures around the circumference of the foramen magnum. Linear fractures of the skull most often are found in the plane in which the force was applied.

Spinal Injuries. Compression vertebral fractures are most often caused by $+G_z$ vertical forces greater than 20 G (usually greater than 26 G), but may occur with forces as low as 10 to 12G. Shearing (or transacting) fractures of the vertebral column can result from horizontal forces of 200 to 300 G.

A combination of G_x, G_y, and G_z forces usually causes the vertebral fractures. The resultant fracture pattern has been described as a "crowbar fracture" with compression of the anterior portion of the vertebra and pulling apart of the posterior bony ligamentous portions in tension. At autopsy, gross lacerations of the brain stem and spinal cord or the vessels covering them and parenchymal hemorrhages within the brain stem and spinal cord may be found.

Certain crash circumstances, coupled with the potential "hangman's noose" formed by a loop consisting of the inferior edge of the helmet, the nape strap, and the chin strap, may produce a fracture dislocation at the axis (C2 and C1) and a fracture of the posterior arch.

Internal Injuries. Because the internal organs are suspended only by attachments within the abdomen and the chest, and are asymmetric in size and weight, they may experience torsional and shearing forces that can produce internal tears. Penetrating injuries may be caused by external objects, parts of the cockpit controls, or broken ribs.

The heart or great blood vessels may be compressed between the sternum and vertebrae and, as a result, rupture. Their rupture may also occur following a compression force to the chest or abdomen that transmits hydrostatic pressure backwards toward the heart. Transverse laceration of the aorta at the root or ligamentum arteriosum is due to traction by the relatively unrestrained heart moving in the chest on any axis. Vertically oriented lacerations of the thoracic aorta are more likely due to lacerations by broken ribs.

Laceration, tears or rupture of the abdominal organs may be produced by blunt trauma to the abdomen. Blunt trauma to either the thorax or abdomen may result in a ruptured diaphragm.

Extremity Injuries. Injuries of the extremities may be caused by impact with surrounding structures or by free or uncontrolled movement (i.e., flailing) of the extremities during the crash sequence. The term "flailing" is usually associated with ejection injuries but can be used to describe injuries in the cockpit. Examples are incapacitating leg fractures caused by upward buckling of the aircraft fuselage, and "dashboard femoral fracture" caused by the knee impacting the instrument panel.

Injury patterns of the hands and feet may be used to identify who was in control of the aircraft, or even if a single pilot actually had the controls at the time of the crash. These injury patterns have been labeled "control injuries." Fractures of the hands may occur in those who are tightly holding the wheel or stick during the crash sequence. On impact the energy transmitted through the pedal controls may fracture the foot. The imprint of the pedal may rarely be transferred to the pilot's boot. In general, fractures of the carpal, metacarpal, tarsal, and metatarsal bones, in conjunction with laceration patterns on the palms and soles, serve as good evidence that the aviator was attempting to control the aircraft.

For further discussion the reader is referred to classic articles on control injuries by Coltart and Krefft. Coltart used the term "aviator's astralgus" to describe fractures of the talar neck in pilots of aircraft equipped with toebrakes. Krefft examined the mechanics of these control injuries. If the pilot has clasped the control stick at the very instant of impact, the area between the thumb and index finger will experience "exceptional strain" caused by the impact jolt. A distinctive stick grip pattern of injury may result that consists of abrasions, contusions, soft tissue tears, or fractures in this area. Similarly, serial transverse fractures of the metacarpals, especially if dorsally displaced, indicate the pilot was gripping the control stick. If the crash force is very violent, the proximal joint of the thumb may become completely crushed or even severed, and fractures of the distal ulna and radius may be seen. This type of hand injury is characteristic of jet aircraft crashes. It should be noted that these control injuries are located on the flexor sides of hands and soles, whereas flailing contact injuries are usually found on the extensor surfaces of the distal limbs. Krefft also discusses how these control injuries are reflected in typical damage to gloves and boots (e.g., tears, characteristic patterns, impression marks, or traces of color).

Ejection Injuries. The main injuries associated with ejections and windblast from high speed ejections are flailing injuries of the head, neck, and extremities that include dislocation, fractures, and maceration. The flailing motion is similar to "cracking a whip" with force being concentrated more distally. This motion produces fractures of the tibia, fibula, radius, and ulna more frequently than of the femur and humerus. The force generated at the anterior edge of the ejection seat may cause femoral fractures. There can also be superficial skin "stretch lacerations" similar to those seen on pedestrians struck by automobiles. During the ejection sequence, the opening shock of the parachute may cause injury if the ejection occurs at high altitude or high velocity or both.

Decelerative Injuries and the approximate G forces involved:

Vertebral body compression fractures: 20 to 30 G.
Tears of aortic intima: 50 G.
Transection of aorta: 80 to 100 G.

Fractured pelvis: 100 to 200 G.
Transection of vertebra: 200 to 300 G. (Through vertebral body, not intervertebral disc)
Total body fragmentation: 350 G or greater.

It is important to base the estimation of decelerative G-forces on decelerative injuries only; the unintentional inclusion of impact injuries in G-force estimation is a common problem.

Impact Injuries: Injuries due to human-machine interaction. These should be related to cockpit/cabin structures by careful examination of both the cockpit of the crashed aircraft and an identical intact aircraft. These injuries consist of blunt force trauma: patterned contusions, abrasions, lacerations, and fractures. There may be transfer of tissue or hair to cockpit surfaces. Flail injuries may result from violent extremity movement in high speed ejection (e.g., Q forces), or may be seen in non-ejection mishaps due to inertial forces. It must be remembered that deformation of the cockpit during the crash may result in a transient, but still fatal, loss of occupiable space. Differential injury (e.g.. primarily left versus right sided injury) assists in determining directionality of forces, as may examination and interpretation of roentgenograms. If the crash is due to mid-air collision with breakup and free-falling bodies, the injuries (if any) due to the collision and aircraft breakup should be differentiated from ground impact injuries.

Intrusive Injuries: Most commonly seen in helicopter crashes, either due to an unbalanced rotor going through the cockpit/cabin, or striking an unseen high-tension wire at speed. Less common are tree strikes. Bird strikes in the cockpit can cause extensive injury to the pilot, including decapitation. Occasionally mid-air collisions result in injury to occupants, as well as aircraft damage.

Thermal Injuries: The most critical issue is determining if the victim was alive in the fire. Artifacts of postmortem fire exposure are discussed below. Differentiating injury from mere artifact is sometimes quite difficult, but always very important, particularly when looking for control injuries.

ENVIRONMENTAL FACTORS

Hypoxia

One of the most important and least readily solved problems confronting aircraft accident investigators is the detection of acute antemortem hypoxia. Hypoxia may occur insidiously (e.g., prolonged flight at altitude) or suddenly (e.g., rapid decompression at high altitude). Lactic acid elevation in brain is theoretically a fairly sensitive and specific test for such hypoxia. Practically, however, this test is really of no use, since such testing requires the intact brain; loss of control due to hypoxia results in a high speed uncontrolled descent with extensive fragmentation on impact. In over 15 years OAFME has not had a single fatal mishap in which hypoxia might have been involved in which there was adequate sample to test.

Fire

In-flight fires can cause streaming patterns of soot deposition on the victim's body and aircraft surfaces. The ignited fuel at impact causes a fireball that can cause first- and second-degree burns of unprotected skin surfaces. It should be recognized that "burning to death" does not occur in crashes: the victims die of impact injuries and/or inhalation of carbon monoxide and other products of combustion well before sustaining burns. Post-crash fire injury patterns can be very difficult to interpret. Distal extremities are often fractured in charred bodies. Differentiation between control injuries and postmortem thermal fractures is often very difficult. It is better to err on the side of thermal fracture than to diagnose a control injury that does not exist.

Soot found in the mouth, nose, or elsewhere in the naso- or oro-pharynx may indicate that the person was alive at the time of the fire. However, this finding is not conclusive. The soot may have been the result of agonal respiratory excursion. Soot in the distal trachea (below the vocal cords) and bronchi is good evidence of inhalation of combustion products. The pathologist may have to examine multiple sections of the trachea and distal airways microscopically looking for soot. This, combined with elevated carbon monoxide levels, would confirm that the victim was alive at the time of the fire. If the victim is exposed to the fireball and inhales the atomized burning fuel, thermal burns of the trachea or even bronchi may be seen. Conversely, exposure to the fireball may result in laryngospasm with no thermal burns below the level of the vocal cords and very low levels of carboxyhemoglobin. Burns seen in the airways of those not exposed to a fireball are generally chemical, rather than thermal, in nature. They are due to the noxious products of combustion from many synthetic and some natural materials.

A carboxyhemoglobin blood level greater than 10 percent usually suggests significant carbon monoxide exposure before death. Levels up to 10 percent can be encountered in smokers (usually 3-6 percent) and levels up to 7 percent may be found in nonsmokers from industrial and metropolitan areas.

In fire fatalities the carboxyhemoglobin level is usually a function of the size of the enclosed space and of the exposure time. In transport aircraft crashes, victims of the fire may have carboxyhemoglobin levels ranging from 30-60 percent. Levels of 10-30 percent are usually seen in fire victims in smaller aircraft crashes. A level of 30 percent generally relates to a survival of 1 to 17 minutes.

Artifacts of postmortem exposure to fire are often misinterpreted by the inexperienced pathologist or investigator. Heat contraction of muscles produces a "pugilistic" appearance with flexed hips, arms, and legs, as if the victims were protecting themselves from the fire. The stronger flexor muscle groups are simply dominating the extensor muscles. Skin splits due to contraction may be confused with lacerations. Burning away of the abdominal wall with extrusion of intestine is often similarly misinterpreted. Skull fractures due to heat (rather than impact) often are "delaminating": the outer table of the cranial bone will flake off, exposing the medullary bone. Further heat exposure results in the inner table and medullary bone flaking off together. The delamination is due to differential expansion of the curved skull as it is heated from without. Epidural hematomas, usually associated with head trauma and skull fracture, are merely an artifact in burned bodies, unless directly related to a linear fracture.
After exposure to heat, hair color observation may be unreliable. Visual impressions of the age of a body cannot be relied upon. Height and weight are similarly unreliable.

Water (Drowning)

In fatal aircraft accidents occurring in water, it is natural to ask whether death was caused by traumatic injuries or drowning. When injuries are severe, the death is traumatic. Drowning should be considered as the cause of death if injuries are minor or not likely to cause death. Some pathological findings (anatomic and chemical) are compatible with drowning. However, no simple finding (autopsy or laboratory) is diagnostic of drowning. A diagnosis of drowning can be made only after excluding all other diagnoses.

In a body recovered from water and thought to have drowned, the only external finding may be a mushroom of froth in the nose and mouth (the "foam cone"). This froth is considered nonspecific but may be highly significant if circumstances suggest drowning. Occasionally petechial hemorrhages may be found in the conjunctivae, most often in the lower eyelids. Rigor mortis may set in early, due to exertion. Some external findings occur after death and should not be confused with premortem trauma. Abrasions may be found on the skin surfaces exposed to the bottom of the body of the water as the drowned body drifts along the bottom. The skin of the hands and feet may appear wrinkled after prolonged exposure to the water. Finally, there may be postmortem mutilation of the body from sharks, crabs, lobsters, fish, turtles, etc. This is initially concentrated around the soft parts of the face (lips, eyes, nose), or around injuries.

Internal findings in most drowning cases include heavy congested lungs secondary to aspirated water and edema fluid. Petechial hemorrhages under the pleura may be seen as well as hemorrhages into the temporal bones.

Unless a drowned body is kept afloat by a flotation jacket or air caught under the clothing, it will sink. Gas is produced by decomposition and the body ultimately rises to the surface. The ability of bacteria to proliferate will determine the time required for the body to float to the surface. Bacteria grow faster in warm water, in fresh water, and in stagnant water and will grow slower in cold water, in sea water, and in rapidly moving water. Obese bodies should rise sooner than lean bodies.

Many controversial chemical tests have been proposed to help with the diagnosis of drowning. They are based on the idea that water was aspirated with alteration of blood volume and electrolytes. Similarly, the presence of diatoms in the lungs has been proposed as a "drowning test". While frequently used in Europe, these tests are rarely used in the U.S. because a thorough investigation of circumstances and examination of the scene has been found to be more reliable than any laboratory test.