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REVIEW ARTICLE

A review of forensic pathologists in aviation pathology and accident investigation

Lii Jye TAN[1,*], Ling Seow NG[2,3], Beng Beng ONG[4,5], Cai Ping KOH[6,7], Mohammad Shafie OTHMAN[1]

[1]Department of Forensic Medicine, Hospital Raja Permaisuri Bainun, Ipoh, Perak Darul Ridzuan, Malaysia; [2]Air Arabia Medical Center, Air Arabia PJSC, Sharjah, United Arab Emirates; [3]Air Accident Investigation Bureau (AAIB), Ministry of Transport, Malaysia; [4]Queensland Health Forensic Pathology and Coronial Services, Queensland, Australia; [5]Faculty of Medicine, The University of Queensland. Queensland, Australia; [6]Faculty of Medicine, Quest International University, Ipoh, Perak, Malaysia; [7]Center for Stem Cell Research, Quest International University, Ipoh, Perak, Malaysia.

Abstract

In Malaysia, aviation accidents fall under the jurisdiction of the Air Accident Investigation Bureau (AAIB) and are subject to statutory investigation. The primary aim of these investigations is to reconstruct crash events, determine root causes, and recommend safety improvements, including modifications to aircraft design, to enhance survivability and prevent future incidents. Aviation pathology plays a crucial role in this process by confirming victim identities, establishing causes of death, contributing to crash sequence reconstruction, and ensuring a comprehensive analysis of human factors. This review examines key aspects of aviation pathology, including injury mechanisms and patterns, the forensic autopsy approach for aviation fatalities, and the correlation between injury findings and crash dynamics. Understanding these elements is essential for improving aviation safety and refining investigative methodologies.

Keywords: aviation pathology, autopsy, aviation accident investigation.

INTRODUCTION

Aviation accidents are rare occurrences; averaging approximately nine incidents per year over the past 11 years in Malaysia, with light aircraft being the most commonly involved.[1] Aviation accidents are subjected to statutory investigation, under the jurisdiction of Ministry of Transport Malaysia, the Air Accident Investigation Bureau (AAIB) is responsible for examining civil aviation accidents and incidents in the country. Established in 2022 as an independent entity, the AAIB consists of experts from various fields, including aeronautical engineers, aviation physicians, pilots, psychologists and other specialists. Their primary responsibilities include collecting, analysing, and assessing all relevant information related to aviation accidents, such as aircraft and wreckage evaluations, flight data and voice recorders, flight operations, maintenance records, and accident scene assessments. The objective of these investigations is to reconstruct the crash events, identify the root causes, and recommend improvements, including modifications to aircraft design, to enhance survivability and prevent future accidents.

In the event of a fatal aviation crash, forensic pathologists play a crucial role during autopsies. Their responsibilities include confirming the identity of the deceased, determining the cause of death, and analysing injury patterns to aid in reconstructing the crash sequence. They also assess human factors that may have contributed to the accident, providing information on the effectiveness of safety equipment and aircraft crashworthiness. Aviation pathology integrates autopsy findings with various aspects of the crash, such as the circumstances of the accident, the pilot's medical history, aircraft wreckage, and the use of safety equipment. This comprehensive analysis supports the AAIB in its investigation, helping to uncover critical insights into the causes and contributing factors of aviation accidents.

**Address for correspondence:* Department of Forensic Medicine, Hospital Raja Permaisuri Bainun, Jalan Raja Ashman Shah, 30450 Ipoh, Perak Darul Ridzuan, Malaysia. Tel: 05-2087358 (LJT); Email: *ilyy812@hotmail.com*

Similar to autopsies conducted for road traffic accidents, determining the cause of death in aviation crashes is often not the most challenging aspect of the investigation. Victims of aviation accidents typically sustain severe traumatic injuries due to the high-impact forces involved, with death commonly resulting from mutilating injuries affecting various parts of the body. The primary challenge, however, lies in identifying the victims and reconstructing fragmented or commingled remains. In some cases, the recovery of human remains may be delayed, leading to advanced decomposition, which further complicates the identification process and forensic analysis.

Given the rarity of aviation fatalities, pathologists without specialisation in aviation pathology may have limited experience handling such cases. Therefore, comprehensive guidelines are crucial to standardise aviation fatality autopsies and ensure that relevant information is gathered effectively to support the AAIB's investigation of fatal air accidents. This review explores key aspects of aviation pathology, including the mechanisms and patterns of injuries, the autopsy approach to aviation fatalities, and the correlation between injury findings and the dynamics of the airplane crash.

1. Factors of airplane crash

The catastrophic effects of an airplane crash highlight the complex interactions of multiple factors that contribute to such incidents. Understanding these factors is crucial for enhancing aviation safety mitigate the risk of aviation tragedies. Key contributors include human factors, environmental conditions, mechanical failures, and organisational shortcomings.

1.1 Human factors

Human error has long been recognised as a significant factor in aviation accidents, with pilot error being one of the most common causes.[2] This can manifest in various ways, such as underestimating critical parameters like weather, terrain, or airspeed, leading to miscalculations that compromise flight safety. In high-pressure or emergencies, poor decision-making can escalate problems rather than mitigate them. Additionally, deviations from standard operating procedures or miscommunication with air traffic control (ATC) can have catastrophic consequences. A notable example is the 2020 helicopter crash that claimed the lives of NBA star Kobe Bryant, his daughter, and seven others. The accident was primarily attributed to pilot error, as the decision to fly into dense clouds resulted in spatial disorientation and loss of control—actions that violated aviation regulations.[3]

Errors by ATC can also contribute to accidents. Miscommunications between pilots and ATC may lead to misunderstandings about critical instructions, while incorrect navigation guidance or clearance can result in disaster. For instance, in 1949, Pennsylvania Central Airlines Flight 410 crashed into Lookout Rock in the West Virginia Blue Ridge Mountains after receiving clearance to descend, leading to the deaths of all 50 passengers and crew members.[4]

Maintenance and engineering errors further exacerbate aviation risks. These issues can arise from improper installation of aircraft components or failure to detect mechanical malfunctions during routine inspections. Inadequate pre-flight checks can allow hidden defects to go unnoticed until they cause mid-flight failures. An example is the 2003 crash of Air Midwest Flight 5481, where inexperienced subcontractor maintenance workers incorrectly adjusted the elevator control cables, leading to insufficient elevator travel during take-off and ultimately causing the crash.[5]

Additionally, failures in Crew Resource Management (CRM) highlight the importance of effective teamwork and communication among flight crew members. Poor coordination or a lack of open communication in the cockpit can impair the crew's ability to respond to challenges, increasing the likelihood of an accident.

1.2 Environmental conditions

Environmental factors, including weather conditions, wildlife hazards, geographical challenges, and air traffic congestion, remain unpredictable threats to aviation safety. These factors can directly impair aircraft performance or indirectly influence pilot decision-making, underscoring the need for effective risk assessment and mitigation.

Weather is the most significant environmental hazard. Turbulence, thunderstorms, lightning, hail and icing can damage aircraft structures, disrupt navigation systems, and reduce lift, potentially leading to loss of control.[6] Low visibility from fog or heavy rain further complicates safe manoeuvring and landing.

High-attitude flight carries physiological risks. At 18,000 feet, oxygen levels are roughly half of those at sea level, and ascending beyond 8,000 feet without supplemental oxygen can lead to altitude sickness. Reduced oxygen levels can cause hypoxia, impairing cognition and potentially incapacitating pilots.[7] Carbon monoxide exposure from exhaust or heater leaks may also contribute to pilot impairment, as well as provide insights into survival duration following a post-crash fire.[8]

Wildlife hazards, particularly bird strikes, can result in engine failure, damage to windshields or obstruct a pilot's vision. Airports, therefore employ monitoring systems and habitat-management strategies to reduce bird activity.

Geographical challenges such as mountainous terrain, high-altitude airports, or short runways require precise navigation and specialised piloting skills. A notable example is the 1992 crash of Thai Airways Flight 311 in Nepal, where weather, terrain, and communication failures contributed to controlled flight into terrain.[9] Volcanic ash poses additional risks; ingestion of ash particles can cause severe engine damage and loss of thrust, while airborne ash reduces visibility and may cause respiratory distress for those onboard.

Airspace congestion increases the likelihood of mid-air collisions. The 2002 Überlingen disaster illustrates how traffic density, air traffic control errors, and conflicting instructions can result in catastrophic outcomes.[10] These examples highlight the complex and unpredictable nature of environmental factors in aviation. Understanding and mitigating these risks through technological advancements, improved training, and stringent safety protocols are crucial to ensuring safer air travel.

1.3 Mechanical failures

Mechanical failures arise from design flaws, manufacturing defects, or wear and tear. Engine failure may result from inadequate maintenance, material fatigue, lubrication problems, or faulty components. Structural defects such as cracks in wings or fuselage compromise airframe integrity, while hydraulic or electrical malfunctions can impair control surfaces, braking, navigation, or communication systems.[11]

Faulty instruments and sensor errors may provide inaccurate altitude or navigation data, leading to pilot misjudgement and unsafe manoeuvres.[11] Landing gear failures whether caused by hydraulic faults, obstructions, or sensor malfunctions, can result in runway accidents. An example is the 2022 Red Air Flight REA203 incident in Miami, where a landing gear collapse caused severe fuselage damage and a post-landing fire.[12]

Robust engineering, regular inspections, and strict maintenance protocols are essential to minimise these mechanical risks.

1.4 Organisational shortcomings

Organisational shortcomings can have a profound impact on aviation safety. Contributing factors include inadequate pilot and crew training, operational pressures that prioritise schedules over safety, insufficient regulatory oversight, and supply-chain issues leading to the use of substandard parts or maintenance materials.

2. Mechanism of injuries

Injury resulting from an aviation crash is fundamentally a consequence of the human body's response to forces applied during the event. The mechanism of airplane crash is essential to understanding the causes of injuries or fatalities. These injuries can be categorised into mechanical and environmental types. Mechanical injuries are further divided into contact injuries and acceleration injuries. Environmental injuries include high altitude environmental hazard, burns (both chemical and thermal), and incidents like drowning.[17]

2.1 Type of airplane crash

When the aircraft collides with the ground, water and other objects, it encounters an opposing force which reduces the initial impact velocity, eventually bringing the aircraft to a complete stop. The kinetic energy of impact is greatly affected by its mass, velocity, angle and duration of impact. Consider an aircraft cruising steadily at its usual altitudes, an unexpected loss of control in a sudden- whether caused by a stall, mechanical failure or pilot disorientation- forces the aircraft into a steep nosedive (FIG 1A). The nose pitches sharply downward, transforming the once-level plane into a plunging projectile descending rapidly toward the ground. This harrowing scenario was exemplified by the tragic case of Germanwings Flight 9525 in 2015, where deliberate human intervention led the aircraft to descend steeply into the French Alps.[13] A primarily vertical deceleration impact is characterised by the injuries to the spine, the hinge fractures of the skull, facial injuries and the aortic ruptures. Mid-shaft femur fractures caused by vertical impact between femur and the seat's front support is commonly seen.[14]

For some, survival hinges on the execution of a belly landing (FIG 1B). Typically caused by landing gear failure or a pilot's decision during an emergency, the aircraft skims its underbelly across the ground. A notable example is LOT Polish Airlines Flight 16 (2011), where the crew safely landed a Boeing 767 with its landing gear retracted.[15] While often survivable, injuries include spinal compression fractures, herniated disc particularly in the lumbar region, caused by vertical forces experienced during a hard landing; perineal, lower limb, whiplash and restraint injuries are common in longitudinal force deceleration.[16,17]

Even routine manoeuvres like take-off and landing hold latent dangers. During an aggressive ascent, over-rotation might result in a tail strike (FIG 1C), the aircraft's tail scraping against the runway with a bone-jarring screech. Such impacts, caused by improper take-off technique or unstable approaches, were evident in Japan Airlines Flight 123 (1985). Though the initial tail strike did not down the plane, it compromised the fuselage, leading to a catastrophic crash later in the flight.[18] A study of the injury pattern (Cullen 1980) revealed that passengers seated in the rear of the aircraft sustained more serious injuries than those in the front, indicating a tail-down impact.[19]

On landing, a miscalculated approach or turbulent weather can cause a hard landing, where excessive force jolts passengers and stresses the aircraft's structure. This was seen in Lion Air Flight 8632 (2013), which suffered a hard landing in Bali due to pilot misjudgement and weather challenges.[20] The pattern of injuries observed is similar to those typically associated with belly landings; however, the overall survivability rate tends to be higher, likely due to factors such as reduced impact forces and the absence of catastrophic structural failures.

Runway hazards extend beyond initial take-off and landing. Skidding or sliding off (FIG 1D) the runway can occur due to failures in braking systems, hydroplaning, or misjudgement of landing speed by pilots. A notable incident illustrating such hazards is Southwest Airlines Flight 1248 (2005), which slid off the runway at Chicago Midway International Airport under snowy conditions.[21] While fatalities are uncommon, injuries resulting from abrupt lateral movements may include sprains, contusions, and fractures.[16]

The water landing, often resulting from engine failure or an emergency decision, as exemplified by US Airways Flight 1549 (2009) making an emergency landing on the Hudson River.[22] While these landings demonstrate remarkable skill, they also introduce unique risks, such as drowning for passengers unable to escape the cabin, hypothermia in cold waters, and blunt force trauma during impact. The tragic case of Ethiopian Airlines Flight 961 (1996) underscores the challenges of such landings, as the aircraft broke apart upon ditching.[23] Evidence of limb-flailing injuries suggested that the aircraft likely experienced at least two impacts with the sea.[19]

The aircraft can become unstable when a wing strikes in midair, which is frequently brought on by strong cross winds or a loss control of aircraft (FIG 1E). This happened on American Airlines Flight 587 (2001), where pilot-induced oscillations caused the vertical stabiliser to fail after initial wing stresses.[24] A flat spin (FIG 1F), where the aircraft spirals around its vertical axis, is a nightmare scenario caused by a stall or improper recovery. One such case was Air France Flight 447 (2009), where a combination of pilot error and automation failure led to a flat spin and subsequent crash into the Atlantic.[25] Such incidents frequently lead to broken bones and severe concussions among the unrestraint passengers.[16]

When impact becomes inevitable, the outcomes are grim. A cartwheel flip (FIG 1G), often triggered by uneven terrain or asymmetric forces, can leave initially survivable passengers at risk of asphyxiation if they remain strapped in their seats while the aircraft comes to rest in an inverted position. This was tragically seen in American Airlines Flight 1420 (1999).[26] Similarly, a breakup on impact, as in Air India Express Flight 812 (2010), results in the disintegration of the aircraft, leaving little chance of survival.[27]

The ultimate nightmare, however, is a breakup in mid-air (FIG 1H), where structural failure, a bomb, or turbulence causes the aircraft to disintegrate. The tragedy of Pan Am Flight 103 (1988), brought down by a terrorist bomb, is a harrowing example.[28] In this instance, the deceased individuals will be dispersed over a wide area at the scene due to the breakup of the plane at altitude, as opposed to a crash involving impact with an object. In-flight explosions can cause haemorrhages in air-filled tissues such as the lungs or gastrointestinal system. Shrapnel can cause several penetrating injuries, and bomb fragments may be found embedded in the tissues. These injury patterns may reflect proximity to the explosion's core, rather than the deceleration injuries associated with ground impact.

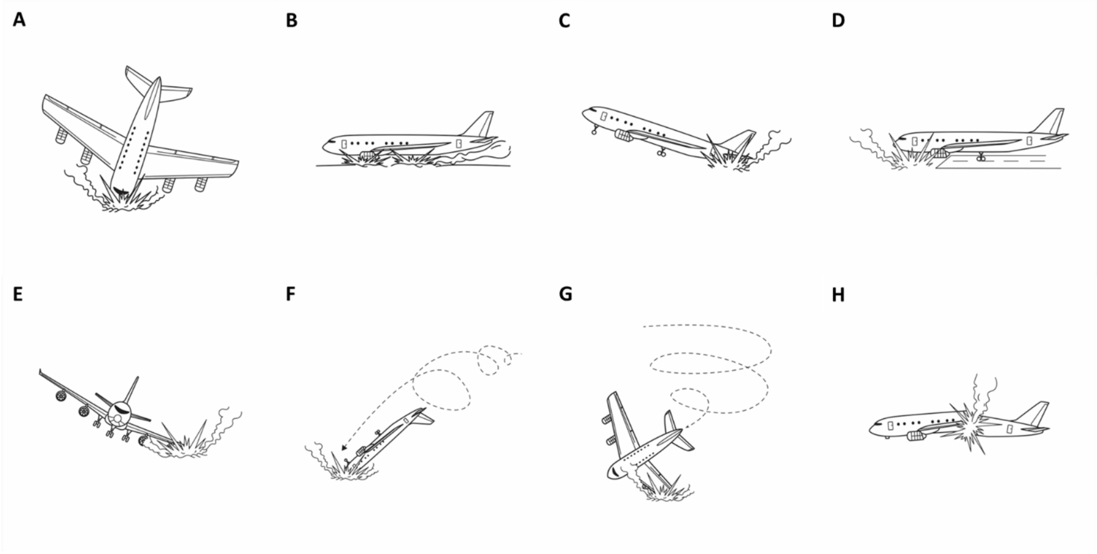

FIG. 1. Graphical representation of the type of airplane crash. (A) Nose dive, (B) Belly landing, (C) Tail Strike, (D) Sliding off, (E) Wing strikes, (F) Flat spin, (G) Cartwheel flip, (H) Mid-air breakup

2.2 Acceleration injuries

Acceleration is the rate of change of velocity of a mass and is typically expressed in units such as meters per second squared (m/s^2). Both force and acceleration are vector quantities characterised by both magnitude and direction. Acceleration or deceleration forces experienced by pilot, passenger or aircraft during rapid changes in speed or direction of flight are commonly referred to as G-force.

Aircraft flight dynamics involve movement along three dimensions: the longitudinal axis (x), the lateral axis (y), and the vertical axis (z). Figure 2 illustrates a standard coordinate system applied to seated pilot. +Gx also known as “eyeball in” or “backward acceleration”, refers to a force acting from chest to back, such as during take-off, when the pilot is pushed into the seat. Conversely, -Gx or “eyeball out” or “forward acceleration”, describes a force acting from the back to the chest, experienced during landing when the pilot is pushed forward into the harness. Both +Gx and -Gx force can compress the chest cavity, impairing the breathing and circulation.[17]

Lateral forces are denoted by Gy. +Gy or “eyeball left” or “left lateral acceleration”, represents a force acting from the right shoulder to left shoulder, while -Gy or “eyeball right” or “right lateral acceleration”, acts from the left shoulder to the right shoulder. These forces are typically experienced during manoeuvres like an aileron roll, where an aircraft performs a full 360-degree rotation around its longitudinal axis.[17]

Vertical forces are represented as Gz. +Gz or “headward acceleration” (“eyeballs down”), occurs during steep ascents when the force acts from the head toward the feet. This can cause blood to pool in the lower extremities, reducing blood flow to the brain and potentially leading to blackouts or loss of consciousness. Conversely,

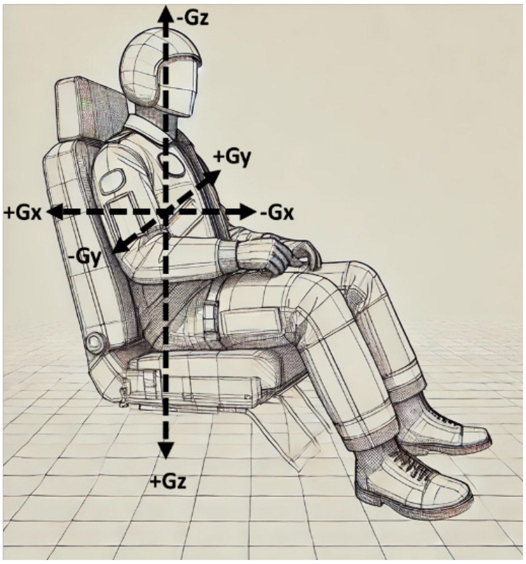

FIG. 2. Direction of G force acting on the pilot

TABLE 1: human tolerance limits of G force.[17]

Direction of acceleration force	Occupant’s inertial response	Tolerance level
Headward (+Gz)	Eyeballs down	20-25G
Tailward (-Gz)	Eyeballs up	15 G
Lateral left (+Gy)	Eyeballs left	20 G
Lateral right (-Gy)	Eyeballs right	20 G
Chest to back (+Gx)	Eyeballs in	45 G
Back to chest (-Gx)	Eyeballs out	45 G

-Gz or “tailward acceleration” (“eyeballs up”), occurs during steep descents, with the force acting from feet toward the head. This can increase intracranial and intraocular pressure, potentially causing haemorrhage in severe cases. Humans tolerate Gx axis acceleration better than Gz-axis acceleration, and tolerances for Gz exceed those for Gy, as shown in Table 1.[17]

Deceleration, commonly referred as negative acceleration, involves a reduction in velocity over time. It is commonly experienced during abrupt stops or impacts, and can cause injuries distant from the point of impact. For example, sudden +Gz deceleration can result in injuries such as ring fracture of basal skull, thoracic aorta ruptures, sacroiliac joint disruptions, lumbar transverse processes fractures, as well as tearing of the mesentery and bowel. The deceleration force needed to cause such injuries has been determined through experimental studies, as outlined in Table 2.[17]

2.3 Contact injuries

Contact injuries are among the most common types of trauma sustained in airplane crashes, and account for more than 75% of fatalities, resulting from the direct impact between the body and surrounding structures within the aircraft. The majority of these cases, approximately 70 to 80%, are due to head injuries.[17] These injuries arise when passengers and crew are thrown against seats, walls, or other interior components due to the crash’s impact. Unsecured cabin equipment, such as bottles and luggage, can also become dislodges and strike occupants. If the body is ejected from the wreckage and comes into contact with external structures such as the ground, mountains, or trees, it may undergo further mutilation or disintegration of body parts. Thoracic trauma is reported in approximately 80% of crash victims, and associated fractures frequently result in severe cardiovascular injury. Nearly half of the victims (47.6%) sustained cardiac rupture, while aortic rupture was identified in about 35% of cases.[17] Abdominal injuries were also common, occurring in more than two-thirds of fatalities. Diaphragmatic rupture was observed in 30.6% of unselected cases, injuries to the liver and spleen were present

TABLE 2: Deceleration force required to cause bodily injuries.[17]

Bodily injuries	Deceleration force
Pulmonary contusion	25G
Nasal bone fracture	30G
Compressive fracture of vertebral body	20-30G
Fracture dislocation of 1st and 2nd cervical vertebrae	20-40G
Mandibular fracture	40G
Maxillary fracture	50G
Intima tear of aorta	50G
Transection of aorta	80-100G
Pelvic fracture	100-200G
Transection of vertebral body	200-300G
Total body fragmentation	>350G

in 42.3%, and renal rupture was documented in 23.5% of victims.[17] Overall, the severity of contact injuries depends on factors such as the crash dynamics, occupant positioning, and the use of safety restraints like seat belts. Typical contact injuries include contusion, abrasion, lacerations and fractures.

2.4 Fire

Fuel dumping, also referred to as fuel jettisoning, is a procedure employed by aircraft before an emergency landing to reduce the aircraft's weight, improving handling and minimising the risk of post-crash fire.[29] Post-crash fires are a frequent consequence of aviation accidents, complicating investigation by destroying the critical evidence and posing a severe threat to occupant survival. Pathologist must first address these challenges by establishing the victim's identity, assessing the vitality of thermal injuries such as blisters and erythema, and identifying any injuries that may have hindered the deceased's ability to escape the fire. The presence of soot below the vocal cords, along with elevated levels of carbon monoxide and hydrogen cyanide in the blood, indicates a period of survival following the crash.

2.5 Drowning

Airplane crashes into water often involve complex interplay of impact forces, environmental conditions and occupant responses. Such accidents can lead to fatalities due to drowning, traumatic injuries or hypothermia. Evidence of unfastened seatbelts or signs of survivors attempting to escape may suggest that individuals were trying to exit the aircraft before or during submersion.

The presence of non-lethal injuries alongside drowning signs, such as a plume of whitish froth from the nostrils, mouth, and airways, Paltauf's haemorrhage, emphysema aquosum, excessive fluid in the stomach, or aquatic organisms and foreign materials like sand particles in the airway and stomach can help confirm drowning. Furthermore, diatom testing in internal organs and bone marrow can provide additional evidence supporting a drowning diagnosis.[30]

2.6 Hyperthermia and hypothermia

Surviving the initial impact of an aircraft emergency landing is a major challenge, yet it often marks the beginning of a harrowing struggle for survival. Stranded in secluded and often hostile environments, survivors face with life-threatening conditions, including extreme temperatures that can lead to hyperthermia or hypothermia, along with the persistent risks of dehydration and starvation. This underscores the critical need for preparedness and resilience in such adversity.

Hyperthermia occurs when the body overheats due to prolonged exposure to high temperatures, often exacerbated by direct sunlight, lack of shade, and limited water availability. Survivors stranded in hot or arid environments are particularly vulnerable, with symptoms including dehydration, dizziness, confusion, a rapid heartbeat, and, in severe cases, heatstroke—a life-threatening condition. Postmortem findings of hyperthermia are non-specific but may include skin erythema or blistering, congestion, oedema, and petechial haemorrhages in internal organs. Additional findings may include subendocardial haemorrhage, right ventricular dilation, contraction band necrosis of the myocardium, histological signs of disseminated intravascular coagulopathy (DIC), centrilobular necrosis as well as sinusoidal dilatation of the liver. Evidence of rhabdomyolysis, such as myoglobin casts in renal tubules, elevated myoglobinuria, and increased creatine kinase levels, may also be present.[31]

Hypothermia poses a severe risk to crash survivors, especially in cold or wet environments where body heat is lost faster than it can be generated, leading to a dangerous drop in core temperature. Exposure to freezing conditions, rain, snow, extreme diurnal temperature shifts or cold water- particularly in mountainous regions or ocean crashes- significantly increases the likelihood of hypothermia. Without adequate clothing, shelter, or heat sources, the danger of hypothermia intensifies. External postmortem features include frostbite on extremities such as fingers, toes, nose, and ears, as well as cherry-red lividity caused by the oxyhaemoglobin accumulation. Extreme pallor or haemorrhage into synovial joint spaces may also be observed. In some cases, paradoxical undressing occurs due to cold-induced hypothalamic dysfunction. Internal findings may include haemorrhagic pancreatitis, focal haemorrhages or erosions in the gastrointestinal mucosa, Wischnewski spots in the stomach, subnuclear vacuolation of renal tubules, and myocardial necrosis.[31,32]

Dehydration is a critical concern for airplane crash survivors, arising from limited access to fresh water, exposure to harsh environmental elements, and physical exertion. Those involved in ocean crashes may inadvertently ingest saltwater, which worsens dehydration by increasing fluid loss through the kidneys. The scarcity of drinkable water, particularly in isolated or open-water environments, compounds the problem. Additionally, the physical and emotional stress of survival- whether staying afloat or attempting to reach safety- raises metabolic demands, hastening fluid depletion.

Environmental factors such as intense sunlight, strong winds, or dry air can further accelerate fluid loss through sweating and evaporation, even in cooler climates. External signs of dehydration include dry, shrivelled skin with reduced elasticity and sunken eyes. Internally, findings may include thick, viscous blood and dry mucosal surfaces in the mouth, oesophagus, and intestines. Microscopic examination can reveal acute tubular necrosis and cerebral oedema. Hypernatremia and elevated urea levels detected through vitreous humour testing may suggest dehydration, though their diagnostic reliability decreases with prolonged postmortem intervals.[31,32]

2.7 Chemical exposure

The risk of chemical exposure following an aviation crash is both significant and multifaceted, posing dangers to survivors, first responders, and investigators. These hazards arise from the release of toxic substances due the destruction of the aircraft and its systems. Spilled aviation fuel can cause skin and respiratory irritation, with prolonged exposure leading to chemical burns or systemic toxicity. When fuel combusts, it produces harmful gases such as carbon monoxide, hydrogen cyanide, and nitrogen oxides, which can result in asphyxiation or poisoning.[17]

Hydraulic fluids, often under high pressure, may leak during a crash, causing skin and eye irritation, as well as inhalation risks, particularly if vaporised by fire. In severe cases, extended exposure can lead to neurological effects.[33] Lithium-ion battery ruptures or fires in modern aircraft release hazardous fumes, including hydrofluoric acid, while damaged electrical components can emit toxic substances such as polychlorinated biphenyls.[34,35]

Additionally, Aircraft construction materials like carbon composites, fibreglass, and metal alloys, when burned or damaged, can release microscopic particles and toxic fumes that irritate the respiratory system and skin or cause long-term health complications. If the aircraft is transporting hazardous cargo- including chemicals, radioactive materials, or biological agents- these substances may be released upon impact, creating both acute and chronic health risks. The presence of residual fuel, pressurised tanks, and volatile cargo also increases the likelihood of explosions and secondary fires, further compounding the dangers to those in the vicinity.[36-38]

2.8 High altitude environmental hazard

High-altitude environments present significant dangers to human physiology, particularly if an individual is ejected from an aircraft. As altitude increases, the atmosphere becomes thinner, resulting in hypoxia, which impairs both cognitive and physical performance. Additionally, extreme cold temperatures can lead to frostbite and hypothermia, while low humidity accelerates dehydration. Exposure to high altitudes also heightens the risk of barotrauma due to pressure fluctuations and increases radiation exposure from intensified cosmic rays.[39] Decompression sickness (DCS) occurs when nitrogen dissolved in body tissues forms bubbles during rapid decompression, causing joint pain, neurological symptoms, and respiratory distress. This condition frequently affects pilots and crew operating above 18,000 feet without adequate pressurisation or oxygen pre-breathing.[40] Commercial aircraft typically cruise at altitudes between 30,000 and 42,000 feet. In contrast, ebullism occurs at extreme altitudes exceeding 63,000 feet (the Armstrong limit), where the low atmospheric pressure causes bodily fluids to vaporise at normal body temperature, leading to severe tissue swelling, subcutaneous emphysema, lung collapse, and circulatory failure.[41]

Pattern of injuries

3.1 Restraint injuries from seatbelt and harness

Seatbelts are a fundamental safety feature in airplanes, designed to safeguard passengers and crew during various stages of flight. Despite their simplicity, seatbelts play a crucial role in minimising injuries during turbulence, hard landings, or emergencies. If a harness is used during a crash, it may leave distinctive injuries on the body surface, such as patterned bruises or abrasions. However, the absence of such injuries does not rule out the possibility that the deceased was not wearing a seatbelt.

Commercial airline passengers typically use 2-point lap belts (FIG 3A), which consist of a single strap across the pelvic region. In a high-impact crash, the upper body may be violently thrust forward, causing the belt to shift upward from the pelvis to the abdomen in a phenomenon known as “submarining.” This extreme flexion over the belt can lead to severe abdominal injuries, including trauma to the liver, spleen, pancreas, mesentery, and intestines. In extreme cases, excessive torso flexion may result in Chance fractures of the lumbar spine. Additionally, the rapid forward motion of the hips and knees can force the lower legs downward and forward, striking the seatback and causing mid-shaft fractures of the tibia and fibula. The head may also lurch forward and collide with the seat frame. The deceleration forces during a crash can led to aortic rupture, while intense abdominal compression by the lap belt may send a surge of blood back to the heart, potentially rupturing the thin-walled right atrium and leading to cardiac tamponade, a phenomenon known as “Hydraulic ram” effect.[17,42]

The chin-to-sternum-heart syndrome, also called thoracic compression syndrome, occurs during sudden forward deceleration (-Gx) when the head is forced downward, causing the chin to strike the sternum. This can result in sternal fractures, cervical spine fractures due to hyperflexion, and injuries to the trachea and oesophagus. If the force transfers from the sternum to the heart, it may lead to contusion cordis or commotio cordis, potentially triggering arrhythmias and sudden cardiac arrest. In worst-case scenario, it can result in cardiac laceration. These injuries can be mitigated by using a shoulder harness.[17]

Cabin crew generally wear 4-point harnesses (FIG 3B), while pilots use 5-point harnesses (FIG 3C). These provide enhanced restraint by distributing forces more evenly, reducing the severity of restraint-related injuries. However, the shoulder straps in these harnesses can cause bruising or abrasions in the shoulder area, and rapid deceleration may lead to clavicle or rib fractures. If the buckle is positioned at the chest centre, it may contribute to sternal fractures. Additionally, if the head and neck are not properly supported, whiplash injuries may occur during sudden deceleration. The presence of harness-related injuries in cabin crew members suggests that they were seated and secured at the time of the accident.[17] In scenarios where an aircraft is struck by a missile or another unexpected event occurs, fewer crew members may exhibit harness-related injuries, as they are typically unrestrained and moving throughout the aircraft during flight.

3.2 Control related injury

In dual-control aircraft, determining which pilot was at the controls during a crash is crucial. Typically, the pilot in command occupies the left front seat. However, in the event of a severe impact, bodies may be displaced, or control may have been transferred to the co-pilot if the captain became incapacitated. Therefore, the presence and analysis of controller injuries serve as vital corroborative evidence in identifying who was operating the aircraft before the crash.

Controller injuries in an airplane crash refer to physical harm sustained by the pilot due to their direct interaction with the aircraft’s controls during the critical moments leading up to and during impact. During flight, pilots maintain their arms in a forward right-angle position, with one hand gripping the control wheel and the other managing the throttles or switches.

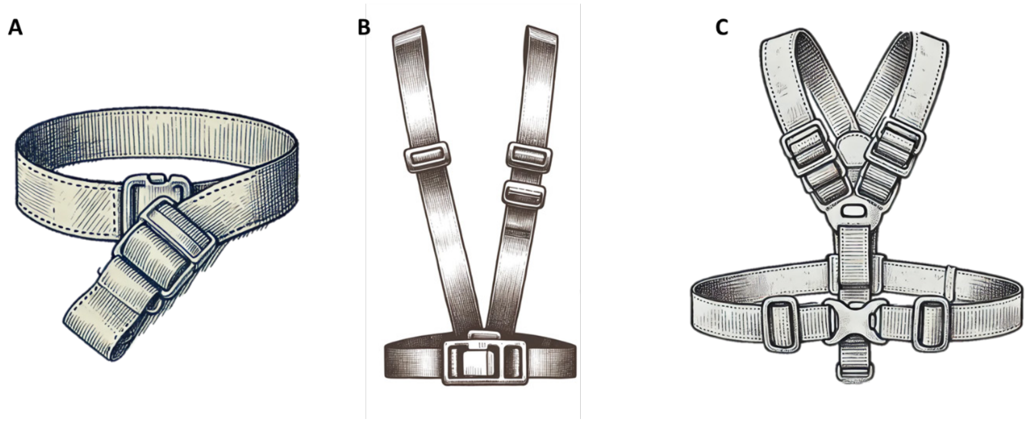

FIG. 3. Type of harness. (A) 2 points, (B) 4 points, (C) 5 points

In fixed-wing aircraft, the control system often consists of a U-shaped yoke, whereas fighter jets and helicopters typically feature a control stick designed to fit comfortably in the pilot's right hand. The area between the thumb and index finger is particularly vulnerable to injury if the pilot is gripping the control column at the moment of impact, often resulting in injury patterns that mirror the shape of the control surface. If the control column fractures, its fragments may become embedded in these injuries. The force from the impact may also be transmitted to the forearm, leading to wrist fractures, dislocations, or displaced fractures of the lower third of the radius and ulna, usually toward the extensor surface.[17,42]

During critical flight phases such as take-off and landing, the pilot's feet rest on the rudder pedals. In a crash, excessive force applied to the soles of the feet, in areas corresponding to pedal contact, often results in injuries to the plantar surface and transverse fractures of the tarsal bones. Conversely, flailing injuries are more commonly observed on the extensor surfaces of the feet and lower legs.[17,42]

The interpretation of control surface injuries should be approached with caution. A study by Campman and Bexfield suggested that these injuries lack sufficient sensitivity and specificity to reliably determine whether an individual was the pilot in control of the aircraft.[43]

3.3 Ejection injury

Ejection from an aircraft is a critical life-saving mechanism primarily used in military aircraft, such as fighter jets, allowing pilots to escape during emergency situations. While this system significantly improves survival rates, it also carries a substantial risk of injury. The ejection sequence begins when the pilot pulls the ejection handle, triggering the jettisoning of the canopy. Explosive charges then propel the seat out of the cockpit. Once clear of the aircraft, the seat separates, and the parachute deploys to facilitate a controlled descent.[44]

Eye injuries during ejection can result from high G-forces, intense windblast, and debris from the canopy jettisoning process. These injuries may include congested eyelids and conjunctivae, conjunctival rupture, and haemorrhaging. Shattered canopy glass can embed in the skin, leading to multiple punctured wounds. Additionally, the explosive charges used in the ejection process can cause burns or blast injuries, while collisions with the seat, canopy, or cockpit frame may inflict further trauma.[44,45]

The rapid acceleration associated with ejection generates extreme vertical G-forces, placing immense pressure on the vertebrae, which can lead to herniated discs or compressive fractures in the cervical and lumbar spine. The weight of a heavy helmet further increases the risk of neck whiplash injuries. High-stress areas of the harness system—such as the scapula, chest, waist, and perineum—are particularly vulnerable to injuries when the parachute opens. These forces can result in visceral trauma, as well as fractures and dislocations affecting the limbs, ribs, spine, and sternum.[44,45]

Windblast injuries occur when sudden exposure to high-speed airflow causes trauma due to the sheer velocity of the wind. These injuries primarily affect the frontal part of the body, leading to facial trauma, rib fractures, and joint dislocations due to flailing limbs. Additionally, hard landings can cause lower limb fractures, sprains, and other impact-related injuries. Adverse weather conditions and rough terrain can further complicate the descent and landing process, increasing the likelihood of injury.[44]

3.4 Other injuries

The "brace for impact" position is designed to reduce forward momentum and minimise injury severity by distributing the force of impact more effectively. For passengers seated in forward-facing seats with lap belts and widely spaced, low-density seating, the recommended bracing posture involves leaning forward, resting the head and chest on the thighs, and gripping the ankles with both hands. While this position enhances the chances of survival, injuries may still occur despite its protective benefits.[46] When properly braced, the head may strike the seatback during impact, potentially causing head or facial trauma. The lap belt can exert significant pressure on the lower thorax and abdomen, increasing the likelihood of rib fractures or internal organ damage. Additionally, as the legs slide backward beneath the seat during impact, this posture may lead to fractures of the tibia and fibula, knee dislocations, and ankle fractures due to the force exerted on the lower limbs.[47]

A ring fracture of the base of the skull is commonly associated with vertical +Gz deceleration along the vertebral axis, as seen in aircraft crashes involving a flat spin in a belly-down position or in hard, upright helicopter landings. In such high-impact scenarios, the lower limbs are more susceptible to injury than the upper body, potentially leaving survivors incapacitated and vulnerable to fatal post-crash fires.[17]

During routine flight, most occupants remain seated with their lower limbs relatively stationary and positioned on the floor. In such cases, inversion and eversion fractures of the ankle can provide crucial information about the direction of impact forces, offering valuable insights into reconstructing the crash dynamics.

Forensic pathologists' approach

Autopsies play a crucial role in aviation fatality investigations, providing valuable insights into the causes and contributing factors of aviation accidents. These medical examinations focus on identifying pathological findings related to the biodynamics of the impact, detecting pre-existing medical conditions, and performing toxicological analyses to rule out environmental hazards or substance abuse that could have impaired the pilot's performance and decision-making. This comprehensive approach ensures that the findings integrate seamlessly with the broader AAIB investigation, offering meaningful contributions to the overall inquiry. It is important to emphasise that determining the cause of death for victims is only one aspect of conducting a full forensic examination; understanding the overall circumstances surrounding the deaths holds even greater significance. Every step of the examination must be performed with meticulous attention to detail to ensure that all available information is accurately documented.

4.1 Scene visit

Scene examination is a vital first step in the investigation of aviation crashes. Whenever possible, the forensic pathologist should visit the crash site to gain a comprehensive understanding of the incident, participate in body recovery, and initiate the victim identification process. The forensic team should not enter the premises until safety has been ensured by the relevant agency, such as the rescue department. The safety of all personnel must be prioritised and maintained throughout the entire process.

Observing the final crash pathway and examining the aircraft wreckage, including factors like post-crash fire or water impact from an aircraft landing, can help pathologists interpret injury patterns and reconstruct the mechanism of injury. Detailed on-site documentation is essential and should include extensive photography, recording the position of victims, mapping the location of remains, documenting seat numbers, the condition of seat harnesses, and the proximity of tissue fragments or amputated limbs to the main body part. An initial assessment of the overall condition of the bodies is crucial for planning mass fatality mortuary arrangements, ensuring adequate storage, and preparing facilities for autopsies.

Clothing and equipment worn by the victims should be preserved and securely stored in the body bag. Special attention should be given to the recovery of aircrew and pilot remains. These remains should be separated from those of other passengers and submitted for more detailed examination at the mortuary. Each body or body part must be assigned a unique identification number, with proper tagging attached to both the remains and the body bag, ensuring it stays with them throughout the autopsy process.

4.2 Information relevant to the autopsy

The flight details, such as the type of aircraft (commercial, military, or helicopter), flight path, crash circumstances (e.g., altitude at impact, in-flight emergencies, or structural failure), carbon monoxide trends in the cockpit or cabin detected electronically, and the mechanism of the crash, are essential for understanding aviation accidents. In the context of an aviation fatalities autopsy, the pilot's autopsy findings play a crucial role in identifying human factors that may have contributed to the crash. The pilot's medical history offers valuable insights into pre-existing conditions, prior treatments, and social factors that might correlate with autopsy findings. Ideally, the pilot's medical records should be obtained from the licensing authority and should include comprehensive documentation of clinic visits, chronic illnesses, surgeries or medical procedures, hospitalisations, allergies, medication history, family medical history, and social history (e.g., smoking, alcohol use, substance abuse, and psychiatric history). The most valuable information often comes from eyewitness accounts provided by survivors. Their statements should be considered in conjunction with postmortem findings and the AAIB investigation to comprehensively study the root cause of the accident.

4.3 Radiological imaging

Postmortem computed tomography (PMCT) represents a significant advancement in the analysis of aviation fatalities. It provides detailed, high-resolution, cross-sectional, and three-dimensional images, enabling a more comprehensive assessment of injury distribution.

This imaging technique preserves the physical integrity of the body and can be completed within minutes, making it particularly advantageous for rapid screening in mass fatality scenarios. PMCT serves as an effective screening tool for detecting embedded foreign objects, such as bullets or shrapnel from explosions. Furthermore, it offers superior methods for identifying air embolism and pneumothorax compared to conventional autopsy techniques. Ideally, CT scanning should be performed on all remains; however, in cases where CT facilities are unavailable, conventional X-ray imaging may be used as an alternative.

4.4 Equipment and clothing examination

Ideally, the clothing and equipment should remain on the body and be transported to the mortuary for detailed assessment. Special attention must be given to clothing, protective garments, life support equipment, harnesses, oxygen delivery systems, gloves, boots, helmets, and masks. These items should be removed carefully, with proper photographic documentation and thorough assessment carried out under the supervision of a pathologist. Evaluating the condition and completeness of this equipment is crucial, as it can provide insights into survivability and crashworthiness. Additionally, observations of bodily injuries may directly correlate with the functionality and crashworthiness of the protective equipment. Jewellery, personal belongings, and military tags can aid in body identification, while clothing may be submitted for toxicology analysis to detect chemical contaminants, if necessary.

4.5 Victim identification

The identification of the deceased following an airplane crash is essential for official and legal purposes, including settling legal claims and repatriating remains to the next of kin. Airplane crashes pose unique challenges, as they often involve a large number of fatalities, with high-speed impacts leading to severe fragmentation of bodies, commingled remains, fire damage, and delays in recovery that result in advanced decomposition, further complicating the identification process.

Identifying the pilot in an aviation crash is of paramount importance for providing critical insights into the cause of the crash. According to Interpol protocols for mass disaster identification, the primary methods of identification include DNA analysis, fingerprint comparison, and dental examination. DNA analysis is a highly reliable technique, especially effective for identifying fragmented body parts and organs. It enables the identification of the majority of tissue and organ fragments, ensuring the completeness of the remains and offering closure to the next of kin. Secondary identifiers serve as supplementary tools when primary methods are insufficient or not feasible. These include personal belongings such as military tags, uniforms, and jewellery; medical implants; tattoos; birthmarks; and circumstantial evidence. Each passenger was assigned a specific seat recorded by the airline, though they might have exchanged seats within the cabin. CCTV footage from the registration counter, boarding gate, and other locations, along with images uploaded to social media before boarding, can offer valuable antemortem data, such as the last known clothing or accessories, to help identify the remains. Circumstantial evidence can significantly ease the identification process by narrowing down potential candidates, thereby reducing the complexity and the number of profiles requiring DNA comparison.

4.6 Autopsy

Autopsies play a pivotal role in understanding aviation fatalities, offering crucial insights that aviation accident investigations and contribute to advancing aviation safety. These procedures, conducted with meticulous attention to detail, aim to determine the causes of death, identify injury patterns, and uncover factors that may have contributed to the crash, such as medical conditions or toxicological influences.

4.6.1 ExtErnal examination

The autopsy process begins with a comprehensive external examination, documenting injuries, burns, or other visible signs of trauma and photography recording throughout the procedure. The preliminary investigation of AAIB will be able to provide the likely mechanism and angle of impact, this information should be correlated with the injuries sustained in order to suggest mechanism of injury and impact sequence, comment about human tolerances and survivability after the injuries.

4.6.2 Internal examination

Detailed internal examination is performed, focusing on organ systems, bones, and tissues. Investigators look for evidence of trauma, such as fractures or organ lacerations, and correlate these findings with known crash dynamics.

This phase is crucial for reconstructing the impact forces and assessing whether injuries were survivable and deciding the cause of death.

4.6.3 Preexisting medical illness

The findings highlight that pilot incapacitation due to preexisting medical conditions is a critical concern in autopsy examinations. However, interpreting natural diseases identified in pilots during autopsy can often be challenging. A pathological finding may serve as the root cause of an accident, act as a contributing factor, or be merely incidental. To simplify the decision-making process, these pathological findings can be categorised as follows: definitely fatal acute pathological findings, potentially fatal acute pathological findings, potentially fatal chronic pathological findings, non-specific pathological findings, and no pathological findings.[48,49]

Conditions classified as definitely fatal acute pathological findings, such as cardiac tamponade due to a ruptured myocardial infarction, a ruptured dissecting aortic aneurysm, or a massive haemorrhagic stroke, inevitably result in death, often irrespective of the aviation crash. However, the possibility of trauma-induced rupture of the myocardium or aorta should also be considered. Coronary artery thrombosis is categorised as a potentially fatal acute pathological finding. Although not immediately fatal under ideal circumstances, such conditions are highly likely to incapacitate a pilot and contribute to a crash event. Potentially fatal chronic pathological findings develop over time and carry a cumulative risk of life-threatening events. Their likelihood of causing pilot impairment is less certain. Non-specific pathological findings, such as epilepsy or hypoxia, may impair critical decision-making or cause sudden collapse. However, these conditions cannot be definitively proven based solely on autopsy findings, and witness reports can provide valuable information to confirm such incidents. Lastly, conditions such as arrhythmias or exposure to extreme G-forces may leave no pathological findings during autopsy but are particularly concerning, as they can result in sudden loss of consciousness without warning. Circumstantial findings, such as the absence of active control of the aircraft and a lack of response to air traffic control, may suggest that the pilot lost the ability to control the aircraft prior to the crash.

4.6.4 Evidence of suspicious injuries

Findings such as gunshot wounds, stab wounds, explosive injuries, or other unusual and unexplained injuries may indicate the possibility of hijacking or terrorist attacks. In some cases, pilots have deliberately crashed aircraft to commit suicide and kill all onboard. A notable example is the Germanwings Flight 9525 tragedy in 2015, which highlighted the catastrophic consequences of undetected psychological illness in the co-pilot. After locking the captain out of the cockpit during a break, the co-pilot initiated a controlled descent, ultimately crashing the aircraft into the French Alps.[13]

4.6.5 Postmortem interval

In most airplane crashes, the timing of death is generally not a significant issue, as the majority of fatalities occur instantaneously. However, when multiple family members perish in a fatal accident, the sequence of their deaths can have implications for inheritance and wealth distribution. The commorientes clause ensures that a beneficiary who does not survive long enough does not have their inheritance included as part of their estate. Determining the time of death postmortem using factors such as body temperature, rigor mortis, livor mortis, or the stage of decomposition is imprecise, particularly when the interval between deaths spans only minutes to hours. Crash-related injuries to vital organs like the brain and heart often result in instantaneous death, while the type and severity of other injuries can influence survival time. Findings such as significant haemorrhage from minor injuries (e.g., a single rib fracture), rhabdomyolysis, fat embolism from soft tissue or fractures, or environmental factors like elevated carbon monoxide levels in the blood may suggest a brief survival period following the crash. Additionally, preexisting medical conditions, such as coronary atherosclerosis or chronic obstructive pulmonary disease, may accelerate death when combined with relatively non-lethal injuries. The toxicology study detected higher levels of carbon monoxide, suggesting that the victim likely survived longer than the others. Circumstantial evidence can also provide clues about survival intervals. For instance, evidence of an unfastened seatbelt, attempts to leave the aircraft, or the use of life-saving equipment or mobile phones may suggest the victim survived briefly after the crash.[17,49]

4.6.6 Histopathological examination

Histopathological analysis of major organs is essential for a comprehensive autopsy examination. Microscopic evaluation can uncover subtle changes or previously undiagnosed medical conditions that could lead to sudden pilot incapacitation, such as remote cerebral or myocardial infarction, myocarditis, cardiac sarcoidosis, or gastroenteritis.

4.7 Toxicology study

Toxicological testing plays a crucial role in aviation accident investigations, involving the analysis of blood, urine, vitreous humour, bile, stomach contents, and other tissues to detect the presence of alcohol, drugs, or carbon monoxide. Identifying these substances helps determine whether impaired judgment, hypoxia, or intoxication contributed to the accident. The toxicological examination of pilots can reveal the presence of substances that may have affected their cognitive abilities, reaction times, or overall performance, potentially leading to the crash. Key substances of concern include alcohol, therapeutic and recreational drugs, and carbon monoxide exposure.

4.7.1 Carbon monoxide

The presence of carbon monoxide (CO) in post-crash victims can indicate whether the individual survived the initial impact but later succumbed to fire-related injuries. Varying levels of carbon monoxide among family members on board may provide insights into the sequence of fatalities. Additionally, cabin contamination from engine exhaust leaks can be a root cause of aviation accidents. The postmortem detection of CO alongside other toxic compounds such as cyanide (from burning plastics), aviation fuel (avgas), and petroleum-based toxins in multiple occupants suggests pre-crash exposure, further supporting investigations into potential in-flight poisoning.[17]

4.7.2 Ethyl alcohol

In Malaysia, the Civil Aviation Authority of Malaysia (CAAM) enforces strict regulations regarding alcohol and drug consumption for flight crew. The Civil Aviation Directive 6007 – Operator Alcohol and Drug Testing Programme sets the permissible Blood Alcohol Content (BAC) for pilots at 0.02%. A blood alcohol level exceeding 20 mg per 100 mL (equivalent to 9 µg/100 mL in breath or 27 mg/100 mL in urine) constitutes legal intoxication. As part of standard procedures in aviation fatalities, blood, urine, and vitreous humour alcohol tests are conducted on all deceased flight crew members. Furthermore, pilots are required to abstain from alcohol consumption for at least 12 hours before reporting for flight duties.[50]

To ensure accurate postmortem alcohol analysis, femoral vein blood samples are preferred over other sources to minimize false-positive results caused by postmortem ethanol diffusion from the stomach. The presence of congener alcohols such as propanol-1, methanol, propanol-2, butanol-1, butanol-2, isobutanol, and methylbutanol-1 (variants 1 and 2) can sometimes result from bacterial fermentation, leading to artefactual alcohol production.[17] In some cases, postmortem alcohol production may exceed 150 mg/100 mL, necessitating careful interpretation based on the body's state of decomposition.[51] To improve accuracy, multiple biological samples should be collected and preserved using sodium fluoride, which prevents bacterial fermentation and ensures reliable test results. Consistent findings across different samples confirm genuine antemortem alcohol consumption.

4.7.3 Other drugs

The detection of therapeutic drugs in a pilot's postmortem toxicology report requires careful evaluation. Certain medications, such as painkillers, antihistamines, and muscle relaxants, may cause drowsiness, dizziness, or delayed reaction times, potentially impairing a pilot's ability to operate an aircraft safely. Similarly, the use of recreational drugs poses a severe risk to aviation safety, as substances such as cocaine, methamphetamines, opioids, and benzodiazepines can significantly impair cognitive function, motor skills, and decision-making abilities.

Despite marijuana being legalised in some countries, its use remains strictly prohibited for pilots, as it can induce euphoria, erratic behaviour, and impaired judgment. Given the high level of responsibility associated with piloting an aircraft, aviation regulations worldwide prohibit the use of illicit substances, ensuring the safety of both crew and passengers.

4.7.4 Toxicology in decomposed remains

Interpreting toxicology findings in postmortem samples presents significant challenges, particularly when decomposition has occurred. Autolysis, which lowers tissue pH, and putrefaction, which generally raises pH, can alter the chemical environment of samples and affect analyte stability.[52,53] As the body undergoes putrefaction, endogenous processes may change drug concentrations through redistribution, degradation, or postmortem synthesis. For example, decomposition can degrade cocaine into benzoylecgonine, or heroin into 6-monoacetylmorphine and morphine, complicating interpretation of the original substance consumed.[52] In addition, bacterial metabolism may reduce or alter concentrations of nitrites, nitrates, and certain volatile compounds, while enzymatic breakdown can affect drugs such as diazepam and paracetamol. Without careful correlation with scene information, autopsy findings, and ancillary analyses such as vitreous chemistry, postmortem toxicology results may be misleading.

Toxicological investigations are essential in understanding the physiological state of pilots and crew members before and during a crash. By analysing biological specimens for alcohol, drugs, and carbon monoxide, investigators can determine whether substance use, intoxication, or toxic exposure played a role in an aviation accident, ultimately improving aviation safety measures and regulatory enforcement.

5. CONCLUSION

Aviation accidents are relatively rare occurrences in Malaysia, and as a result, most forensic pathologists have limited exposure to aviation-related fatalities throughout their careers. Consequently, they may lack familiarity with the specialised autopsy techniques and investigative principles required for aviation accident examinations. However, aviation pathology plays a critical role in determining the cause and manner of death, correlating injuries with crash dynamics, reconstructing the sequence of events, and assessing the significance of human and environmental factors in the accident.

A forensic pathologist's final report should provide comprehensive and scientifically supported conclusions to assist aviation authorities in accident investigations and ensuring accountability. It is essential that autopsy findings be interpreted with expertise and experience, ensuring that injuries, toxicological results, and pathological evidence are accurately analysed within the context of aviation trauma. Therefore, I have summarised the special considerations in approaching aviation fatalities in Table 3. By employing a scientific, evidence-based approach, aviation pathology investigations contribute to identifying root causes, enhancing flight safety, and preventing future aviation disasters.

A complete investigation of a fatal aviation accident requires a collaborative, multidisciplinary approach, integrating findings from aircraft wreckage analysis, flight data recorders, meteorological conditions, and eyewitness testimonies. Aviation pathology serves as a key component of this investigation, ensuring that human factors are thoroughly examined and contextualised within the broader crash analysis. This comprehensive and systematic approach ensures that every detail is meticulously examined, contributing to a better understanding of accident causation and the development of future preventive measures to enhance aviation safety and reliability.

Despite ongoing improvements, several constraints continue to affect the consistency and depth of forensic investigations following aviation incidents. These include limited availability of specialised forensic aviation pathologists, variability in access to advanced

TABLE 3: Summary of special consideration in approaching the aviation fatalities

Information relevant to the autopsy	General questions	- Who was involved? What happened? Where did it take place? When did it occur? Why did it happen? How did it happen?
	Type of aircraft	- Military, commercial, private aircraft, rotary-wing (helicopter), fixed-wing, glider
	Fitness to fly	- Medical and psychiatric background evaluations should be reviewed through the family physician or aviation physician.
	History of past medical illness	- Identify major or minor medical factors contributing to the crash, including preexisting cardiovascular, neurological or respiratory diseases, and other illness
	History of substance abuse	- Alcohol, illicit drugs use.
	Risk of suicide	- Review history of self-harm, psychiatric follow ups, suicide notes and depressive mode.
Radiology study		- Full body radiology imaging of pilot and co-pilot (e.g. CT scan, MRI, X-ray) - Examine for foreign body, fracture patterns, air embolism and pneumothorax.
Clothing and equipment examination	General	- Photography, detailed examination and documentation of clothing and equipment.
	Safety equipment	- Assess potential failures of the safety equipment such as harness and helmets.
	Identity	- Determine the identity of deceased.
Identification	Primary identifiers	- Fingerprint, DNA analysis, dental examination
	Secondary identifiers	- Physical appearance, clothing, personal effects, medical records (e.g. implant from previous surgeries)
	Circumstantial findings	- Collection of antemortem and circumstantial evidence: CCTV footage and photo from social media before departure. - Priority in identification: Identify the pilot, co-pilot and aircrew first.
Autopsy	Evident of foul play	- Rule out suspicious injuries inconsistent with an aviation crash (e.g. gunshot wounds, blast injury, stab wounds) - Identify old and new self-inflicted injuries (e.g. hesitation marks).
	Mechanical injury	- Identify acceleration and deceleration injuries - Assess for thoracic compression syndrome - Document patterned injuries such as restraint injuries, control-related injuries and ejection injuries. - Analyse the distribution and pattern of injuries to infer the crash mechanism and sequence of events. - Determine whether injury distribution suggests specific impact scenarios (e.g. nose-down collision, crash landing). - Use an injury scoring system for severity assessment
	Environmental injury	- Assess incapacitation evidence, such as lower limb fractures. - Evaluate survivability from initial crash impact. - Identify thermal injuries, drowning, hyperthermia, hypothermia, dehydration, starvation and chemical exposure.
	Time of death and survivability	- Assess postmortem changes - Assess the severity of injury and evidence of developing its complications. - Testing carbon monoxide's level. - Determine circumstantial evidence of survival from initial impact and sequence of their deaths (e.g. unfastened seatbelt, activation of life saving equipment)
	Causative, contributory factors in aviation crash	- Identify preexisting medical conditions. - Categorise fatal pathologic findings - Determine pathological evidences contributing the crash - Measure pilot's naked body weight (overweight, obesity). - Conduct detail gross and histopathological examination of internal organs.

Toxicology	General	- Analyse blood, urine, vitreous-humour, bile, stomach content and organs for toxicology analysis
	Carbon monoxide & other hazards	- Conduct quantitative analysis of carbon monoxide level to determine environmental hazards, pilot incapacitation, survival post-impact, and fire-related fatalities. - Screen for other environmental hazards and poisoning
	Risk of impairment	- Test for prescription drugs, recreational drugs, alcohol
Opinion	- Determine the cause of death. - Provide the opinion on the manner of death. - Correlate injuries with crash dynamics. - Reconstruct the sequence of events. - Assess the significance of human and environmental factors contributing the crash - Evaluate survivability potential based on injuries and impact forces. - Contribute to aviation safety and accident prevention through regulator changes, safety enhancements and crashworthiness studies.	

diagnostic tools such as postmortem CT imaging, and differences in inter-agency coordination between forensic units, aviation authorities and investigative bodies. Resource constraints may also impede timely deployment to remote crash sites, resulting in delayed recovery and compromised specimen integrity. Additionally, the absence of comprehensive national guidelines specific to forensic aviation pathology contributes to variations in reporting standards and the interpretation of injury patterns. Acknowledging these limitations highlights the need for enhanced training, improved infrastructure and the development of unified protocols to strengthen the overall quality and reliability of aviation-related forensic investigations in Malaysia.

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