The Head Injury Criteria and Future Accident Investigations

JM Davies, Professor of Anesthesiology, Perioperative and Pain Medicine, Cumming School of Medicine and Adjunct Profesor of Psychology, Faculty of Arts, University of Calgary, and ISASI Associate Member
WA Wallace, Professor Emeritus, University of Nottingham, UK
CL Colton, Professor Emeritus, University of Nottingham, UK
O Tomlin, Engineering Director, GRM Consulting Ltd, UK
AR Payne, Crashworthiness Engineer - Retired, UK

Professor Jan Davies
has undertaken system safety research in healthcare and aviation since 1983. She spent over a decade visiting the (former) Bureau of Air Safety Investigation, co-developing with the late Dr. Rob Lee a human-factors-based, systematic method for investigating anesthesiology-related deaths. Her work has focused on applying aviation-safety concepts to healthcare, including both reactive and proactive investigation methodologies, system safety and quality management, and a healthcare-specific version of the Just Culture. In 2013 she started to research the passenger and crew emergency brace positions and now chairs IBRACE (the International Board for Research into Aircraft Crash Events.)

Introduction

As we look back at ISASI's first 50 years, we instinctively remember the numerous investigations carried out during that period by its members and others, as well as more distant investigations. The first ISASI Seminar was held in 1969, a busy year for accident investigators, with (at least) 50 accidents involving commercial passenger aircraft. (1)

Previous investigations

Some 61 years before that, Orville Wright undertook a demonstration flight at Fort Myer, Virgina, with Lieutenant Thomas E. Selfridge as a passenger. Selfrige was also a pilot and aircraft designer, as well as a passenger on the "first recorded passenger flight of any heavier-than-air craft in Canada" and the "first US military officer to pilot a modern aircraft". (2)

At a quarter past five in the afternoon of September 17, 1908, Wright and Selfridge were on their fifth circuit of the Fort Myer base and at an altitude of about 150 feet, when they heard two loud thumps: the righthand propellor broke off. The plane lost thrust and Wright shut off the engine, gliding down to about 75 feet. A vibration was felt. Part of the propeller hit a guy wire that braced the rear vertical rudder, which then swiveled to horizontal. Wright lost control of the plane, which nose-dived into the ground. Both pilot and passenger were entangled "in a twisted mess of wood, wire, and cloth". (3)

Wright was rescued first and was carried by stretcher to the base's hospital, while efforts continued to extricate Selfridge from the wreckage. Sadly, Selfridge died some hours later. Following Selfridge's extrication from the wreckage, what remained of the aircraft was moved to a large balloon hanger. During his seven-week hospitalization, Wright investigated the crash, having his two assistants take pieces of the wreckage to him. He was able to find the cause of the accident and to explain his conclusions to the Army. (His was, in a way, also the first investigation of a passenger fatality.) The investigation led to safety recommendations and changes to the next Wright aircraft, using the 35 HP engine (4) salvaged from the wreckage and shortening the wings by two feet.

Since that accident in 1908, investigations themselves have changed. No longer is the pilot who flew the craft the principal investigator, and formal additions have been made to investigation guidelines and protocols, one of the lastest being Cabin Safety Investigations. (5)

Survivability

Many investigations have resulted in aircraft-design improvements, some of which have contributed to increased crashworthiness, or how well an aircraft protects its cabin occupants in the event of an accident. This requires that crash forces remain below human tolerance limits and the on-board environment provides a liveable volume.

A ‘survivable’ accident is defined as one “where there were one or more survivors or there was potential for survival”. (6) However, a survivable crash does not mean that all passengers and crew will actually survive the accident. Factors that determine passengers’ and crews’ survival include the **C**ontainer, the **R**estraint system, the **E**nvironment, **E**nergy Absorption and **P**ostcrash Conditions, or **CREEP**. (7) Of these five factors, the second, third and fourth can be affected by the design and subsequent testing of new aircraft cabin interiors. The latter are bound by regulations developed by the European Aviation Safety Agency (EASA) and the Federal Aviation Authority (FAA), amongst others.

One of the earliest accident investigations for survivability factors was that of National Airlines 101 on February 11, 1952. In that accident, a DC-6 crashed shortly after take-off from the Newark, New Jersey Airport. The pilots were unable to return to the airport and the plane, while in a partially controlled descent, hit the roof of a low-rise apartment, skidded, and landed on the ground at about 140 mph and at an angle of 10-15 degrees nose-down. The airplane bounced, cartwheeled and broke into three main parts. The front section of the plane “disintegrated” while the back section was torn loose from the wing section and crashed against and into a large tree trunk at a distance of 280 feet from the initial ground impact point. (8)

In the Introduction to his report (9), Hugh de Haven, one of the two men[i] credited with coining the term ‘crashworthiness’, suggested that there could be a class of accidents that “could be termed survivable, or at least partly survivable”. He went on to say that “such accidents usually involve impact speeds, deceleration distances, structural damage and impact forces which can be tolerated by human beings without fatal or dangerous injury”. The report’s author, Howard Hasbrook, stated that the severity of an accident should not be based solely on the “overall destruction” of the aircraft, using a short description of Flight 101’s crash: “Complete disintegration of major portions of the passenger cabin - followed by fire - a six hundred foot wreckage pattern and a 140 mph impact speed”. Rather, Hasbrook reasoned that should “some portion of the cabin” remain “reasonably intact”, then “information of value for the use of design engineers” could be obtained from accidents such as these. He gave the relevant survivability-related factors, but first on his list was the “known ‘crashworthiness’ of human structure”. (8)

Of the 27 passengers who suffered fatal injuries, half had both skull and rib fractures, one-third had skull fractures only and about 10% had either rib fractures or internal injuries. Eight survivors had “dangerous injuries” (defined as “life-threatening” even with “prompt medical care”). These included skull and rib fractures, internal injuries and long bone fractures. Nearly 90% suffered concussions. Nine of the passengers and the sole (female) cabin crew member had minor or no injuries. Minor injuries included “bruises, contusions and/or lacerations”, with four having no injuries whatsoever. Two of those without any injuries apparently then “took a taxi to the airport immediately after the accident and boarded another airplane to their intended destination”. (8) This report demonstrates the variability of human ‘crashworthiness’, as well as the potential psychological resilience.

The injuries suffered by the survivors were classified according to a scale that was “based on observations during first 48 hours after injury and previously normal life expectancy”. (See Table 1) This scoring system was developed by De Haven for review of survivors of light plane accidents (9) and then applied to traffic accidents by the Cornell Injuries Research Group. (10) Both scales were considered forerunners of the Abbreviated Injury Scale (AIS), developed by the American Medical Association Committee on Medical Aspects of Automotive Injury in 1971. (11)

The AIS is an “anatomically based consensus-derived global severity scoring system that classifies each injury in every body region according to its relative severity on a six-point ordinal scale”, from minor, moderate and serious to severe, critical and maximal, with the latter being considered “currently untreatable”. The body is divided into nine regions, from the top downwards: head, face, neck, thorax, abdomen, spine, upper extremity, lower extremity, external and other. (12) The Injury Severity Score (ISS) is a mathematical derivation from the AIS (13) and these scores are used in the measurement and study of injuries, for example, over time.

Injury Criteria

Development of the AIS was an important advancement in aviation crash survivability. One of the parameters used in the testing process is that of ‘Injury Criteria’. This was originally derived for the automobile industry from multiple experiments, including both cadaveric and animal studies (and their autopsy results). Some studies of human tolerance employed human volunteers, all of whom were likely to be (male) military personnel, who, though tested at sub-injury thresholds, would have also demonstrated involuntary muscle tension and reflexes. (14) (These studies generated measurements of “voluntary human tolerance”, rather than “injury criteria”.) (15) The introduction of Anthropomorphic Test Devices (ATDs), as human surrogates, allowed the use of invasive, rather than superficial, test monitors, the results from which could then be correlated with computer simulations carried out in parallel. Engineering parameters and injury forces became measurable, and statistical calculations could be used to determine “human injury tolerance levels”. Injury test results were then classified according to the degree of severity of the injury in the 1990 AIS Manual, with “no injury” representing the “absence of injuries or minor injuries of AIS<3” and “injury” representing “serious injuries of AIS>3”. (14)

Injury criteria were first applied to aviation in the early 1980s, after a working group of the General Aviation Safety Panel (GASP) recommended crashworthiness improvements for general aviation aircraft. At the top of the list were dynamic testing of seats and restraint system performance, and results from aviation accidents proved helpful. Injuries seen in cars, such as those from the steering wheel, would not be seen in aviation, as the aircraft control column is not fixed – otherwise it would not function. (15) Studies from aviation, such as Coltart's review of 25,000 fractures and dislocations, in patients treated by surgeons working in Royal Air Force orthopaedic units between 1940 and 1945, focused on injuries to the talus bone in the ankle. The specific mechanism in many of these injuries was from the force of the plane's impact with the ground, with the pilot's "sole of the foot resting on the rudder bar". The impact pressed the rudder bar "into the instep just in front of the heel", with the talus then fracturing as it took the brunt of the force. (16) Other military experience also contributed: reducing deaths from one source, for example, by providing effective upper body restraint, meant that non-fatal injuries, such as those to the spinal column, would become more frequently observed. All of these factors contributed to the development and inclusion of injury criteria for the GASP recommendations. (15)

To return to the crash of 1908, Orville Wright suffered a fractured left thigh, a damaged hip and several fractured ribs. His seven-week hospitalization was standard at that time for the treatment of femoral fractures, which would have been immobilized in a resting splint with the leg in traction for six weeks, during which time he was confined to bed. After that, Wright would have gradually been allowed to bear weight on that leg, possibly wearing a weight-relieving caliper, or a hip spica. Despite standard treatment, Wright's back and 'damaged' hip affected him for the rest of his life. In those days, x-ray techniques were relatively unsophisticated. Although his femoral fracture would have been clearly visible on an x-ray of the femoral shaft, it would have been easy to miss a fracture through the acetabulum of the hip, which later could develop arthritis. He might also have suffered one or more compression fractures of his spine at the time of impact with the ground.

Wright's Abbreviated Injury Scale (AIS) Score for those injuries would have likely been 3 for the long-bone fracture of the femur (Extremities). (In actuality, his AIS could have been either 3 if the fracture were 'closed' or 4 if the fracture were 'open', because, in 1908, an open (or compound) fractured femur was a life-threatening injury.) Similarly, his AIS for any bruises or abrasions, for example, over his lower back would have been 1. (17)

Head Injury Criterion

The Head Injury Criterion (or HIC) is an excellent example of another useful Injury Criterion. Basically, the HIC expresses the likelihood of someone's developing a head injury from an impact. Although HIC is now derived from measurement of acceleration over time by an accelerometer placed at the centre of gravity of an ATM's head, (18), HIC was initially derived from studies in 1960 of short duration impacts on human cadaveric heads to produce linear skull fractures. These studies were followed by those using human volunteers and animals. In 1965, data analysis produced a plot of acceleration versus pulse duration, known as the Wayne State Tolerance Curve, and from which the HIC was derived. (15) Further calculations were performed and cumulative distribution curves were constructed to give the probabilities of skull fracture and brain damage. (19) These showed that a HIC of 1500 was considered "too high an apparent risk of brain damage/skull fracture" (at 56%), with seven of 10 tests showing HIC scores of 1000-1500 and "brain damage". (19) At a HIC of 1000, the probability of a "life-threatening" head injury (AIS 4) has been quoted as being either 16% (19) or 18% (20). This can be interpreted to mean “for a group comprised of 50th percentile U.S. males subjected to the collision”, some 16-18% “would not be expected to survive”, with the remaining 82-84 % suffering non-life threatening injuries. (20)[ii]

Current aviation design and testing regulations, and acceptable means of compliance, for example, the FAA Advisory Circular AC No: 25.562-1B, of 2015, (21) stipulate a HIC of 1000 when testing new equipment, e.g., seat-back entertainment systems. A score above 1000 fails, whereas a score of 999 passes (and with only one test run). What does this mean for passengers? At a HIC of 900 - 1254, the Prasad-Mertz curves show that the average adult passenger has a 90% probability of suffering an AIS 2 or ‘moderate’ head injury, which means that the passenger could be unconscious for up to an hour and have a linear skull fracture. The probability that the same passenger could have a serious head injury (AIS 3) is 55%, which would render the passenger unconscious for 1-6 hours and with a depressed skull fracture. (18)

Thus, these current aviation regulations may not truly reflect passengers’ or crews’ injuries and survivability in a crash. Airlines, and aircraft and aircraft seat manufacturers spend millions of euros, pounds and dollars to show compliance with the regulations. Yet, a HIC score of 1000 and its associated clinical states suggest that the next part of the regulatory requirement – FAA mandated passenger evacuation in 90 seconds (22) – could not possibly be met. Thus, by not assuring passengers’ consciousness, the current regulations could feasibly result in unconscious passengers being unable to exit the aircraft to a place of safety and thus succumbing to their injuries.

Over 50 years ago, the need for that part of the regulation was clearly described by John Swearingen from the Office of Aviation Medicine, Federal Aviation Authority: “*In airline crashes it is important for the passengers to remain conscious so that they can escape rather than be asphyxiated or burned to death even though otherwise uninjured*.” He followed this with recommendations to mold seat backs and serving trays of “light aluminum sheet or other material that will deform at loads less than 30g and contour itself to the head and face”, as well as padding “all exposed areas with sufficient slow-return foam to aid distributon of the impact force over the contour of the face”. (23)

The principle behind Swearingen’s statement has been known since (at least) the time of Hippocrates. In about 400 BCE, he wrote: “Of those who are wounded in the parts about the bone, or in the bone itself, by a fall, he who falls from a very high place upon a very hard and blunt object is in most danger of sustaining a fracture and contusion of the bone, and of having it depressed from its natural position; whereas he that falls upon more level ground, and upon a softer object, is likely to suffer less injury in the bone, or it may not be injured at all.” (24)

The HIC in aviation contrasts markedly with that in the UK railway industry, [iii] where the HIC is set at 500. (25) Above this level, at an HIC of 520-899, passengers might be unconscious for less than an hour. (20) The railway injury experts further recommended that the HIC be lowered to 150 in order to reduce the risk of temporary confusion which might prevent movement to a place of safety. (25) At an HIC of 135-519, passengers could have no more than a headache or dizziness while still being able to move away from smoke, fire or water. (20) (See Table 2.)

Again, returning to the crash of 1908, Selfridge was not as fortunate as Wright. Selfridge was finally extricated from the wreckage, unconscious and bleeding and also taken to Building 59, which functioned as the hospital on the Fort Myers base. X-rays in those days would not have helped diagnose the cause of Selfridge's state of unconsciousness. But in various articles, he is described as having a basal skull fracture, most likely a vertical deceleration injury, with midbrain damage. Diagnostic criteria for this injury include a depressed level of consciousness, bruising around the eyes (giving what is described as 'racoon eyes'), bleeding from the nostril and bleeding from the ear. These three latter signs indicate bleeding inside the brain, possibly from damage to the internal carotid artery inside the skull. Sefridge underwent an operation, presumably to attempt to control the bleeding but died on the operating table. His AIS score was therefore 6, although on admission to the hospital it might have been as low as 3 or 4. He was 26 years old. However, his death was not completely in vain as, after this, the "first Army pilots were required to wear helmets similar to early football helmets in order to minimize the chance of a head injury like the one that killed Selfridge". (26)

Application to Future Investigations

How do the HIC and other Injury Criteria apply to the future of crash investigations? To connect the Injury Criteria from the crash impact laboratory with human passengers' and crews' injuries, or deaths, clinically qualified individuals must be able "to compare the kinematics of real people in real collisions with that of dummies in comparable collisions". (18) These experts therefore need access to complete accident reports. For example, the lowering of HIC to 500 for the UK railways and the making of further recommendations to a HIC of 150 came from accident investigation reports reviewed by a team that included clinically-qualified individuals (27). Similarly, development of the 'Kegworth' variant of the emergency brace position came from clinical (28,29) and laboratory (30-34) studies of the Kegworth accident. (35)

Thus, these clinical investigators need access to complete investigation reports that include information such as seating charts and individual-specific descriptions of injuries and fatalities, as well as (any) brace positions adopted, (36) in order to enable them to add their clinically and forensically-evidenced reviews. These reviews could then be either included in the official accident report, or in a separate publication, as with the report by Hasbrook in 1952. (8)

The loss of an aircraft with its potential loss of life, or severe injuries, is a horrible and traumatic event for all concerned. It is therefore imperative that every possible piece of information be gleaned, not only the technical and procedural factors to minimize recurrence, but also the clinical and forensic data, wherever possible, from fatalities and survivors. Nor should psychological data be excluded. Questionnaires and interviews after an accident can help provide information about such concepts as why passengers do not pay attention to safety briefings, (37) passengers' choice of exit (38) and atitudes focused on surviving (39). All these factors will contribute to a better understanding of cabin safety, and passenger and crew survivability. This is not a new concept and has contributed greatly to the advances made in automobile safety-related designs. (18)

We owe our best efforts to help those who are healing and grieving to see that there may be some good from the bad, and the possibility of minimizing future events. We must continue to remember all those who were lost. In doing so the **past will not become irrelevant** but an ongoing reminder of what we need to accomplish: to ensure that **the future of accident investigations** includes clinically-applicable, systematic cabin safety studies that continue to improve passenger and crew survivability.

Table 1. Classification of injuries (Adapted from Appendix 1: Scale used by Crash Injury Research in Classifying "Degree" of Body Injury) (Adapted from Reference # 8).

Type	**Degrees of Injury**	**Description**	**Examples**
A. Minor or None	1	None	No injury
	2	Minor	Contusions, lacerations, abrasions. Dazed or slightly stunned. Mild concussion (no loss of consciousness).
B. Non-Dangerous	3	Moderate	More severe contusions, lacerations, abrasions in any area(s) of the body. Simple factures of long-bones, jaw or cheeks. Concussion less than 5 minutes and notother brain injury
	4	Severe - but not dangerous (Survival normally assured)	
C. Dangerous-to-life	5	Serious - Dangerous (but survival probable)	
	6	Critical - Dangerous (survival uncertain or doubtful)	
D. Fatal	7	Fatal - within 24 hours of accident	Fatal lesions in single region of the body, with or without other injuries to the 4th degree
	8	Fatal - within 24 hours of accIdent	Fatal lesions in single region of the body, with other injuries to 5th or 6th degree.
	9	Fatal	Two fatal lesions in two regions of the body, with or without other injuries elsewhere
	10	Fatal	Three or more fatal injuries - up to demolition of body

Table 2. Head Injury Criteria (HIC), comparable injuries and AIS Score (Adapted from Reference # 20)

Head Injury Criterion	**Comparable injuries**	**AIS Code**
>1860	Non-survivable	**6**
1859 **1575**	Unconscious > 24 hours; large hematoma	**5**
1574 **1255**	Unconscious 6-24 hours; open skull fracture	**4**
1254	Unconscious for 1-6 hours; depressed skull fracture	**3**
1000	***Current aviation limit for acceptable HIC test results***	
900	Unconscious for 1-6 hours; depressed skull fracture	
899 **520**	Unconscious for < 1 hour; linear skull fracture	**2**
519	Headache or dizziness	**1**
500	***Current UK railways limit for acceptable HIC test results***	
150	***Recommended UK railways limit for acceptable HIC test results***	
135	Headache or dizziness	
(<135)	No head injury	**0**

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[i] The other man was John Lane, of the Australian Department of Civil Aviation, who stated in 1949 in relation to aircraft safety that “it was time we stopped considering only whether an airplane was airworthy; [but also] whether it is crashworthy”. (40)

ii In the automotive industry there are different HIC tolerance levels for different size occupants, for example, as used in Federal Automotive legislation for frontal FMVSS208 and side impact FMVSS208, where 5%ile female ATDs are used.

[iii] It should be noted that slightly different time windows over which HIC is measured are used in the automobile, rail and aviation industries. The automobile industry uses as 15 mseconds, termed as HIC 15 msec or HIC(15) when assessing direct head impacts on rigid surfaces and 36 mseconds or HIC 36 msec of HIC(36), for comparing airbags impacts and in some New Car Assessment Programme assessments. The rail industry uses HIC(15), as in the UK Rail Group Standard GM/RT2100 and European Rail Technical Recommendation TECREC. The aviation industry uses neither the HIC(15) or the HIC(36) but the actual head contact time.