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RTO EDUCATIONAL NOTES **EN-HFM-113**

Pathological Aspects and Associated Biodynamics in Aircraft Accident Investigation

(Les aspects pathologiques et la biodynamique associée dans les enquêtes sur les accidents d'aéronefs)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Human Factors and Medicine Panel (HFM) presented on 28-29 October 2004 in Madrid, Spain.

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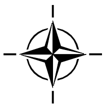

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

AVT	Applied Vehicle Technology Panel
HFM	Human Factors and Medicine Panel
IST	Information Systems Technology Panel
NMSG	NATO Modelling and Simulation Group
SAS	Studies, Analysis and Simulation Panel
SCI	Systems Concepts and Integration Panel
SET	Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Pathological Aspects and Associated Biodynamics in Aircraft Accident Investigation

(RTO-EN-HFM-113)

Executive Summary

The Human Factors and Medicine Panel of the RTO organized the LS-113 on “Pathological Aspects and Associated Biodynamics in Aircraft Accident Investigation”, to review the status and future directions related to effective crashworthiness design and design criteria of aircraft and how such new design interfaces with some critical aspects of the aircraft accident investigation preferably those related to forensic pathology, biodynamics of injury, injury mechanism, injury mitigation and their implications for flight safety in relation to any type air based platform.

These Lecture Series (LS) will be focused on determining what injury and injury mechanism data are required from accident investigations and will make recommendations on effective techniques and methodologies to use in the conduct of an accident investigation.

The purpose of this LS is to address the above mentioned critical aspects of the investigation and discuss specific issues such:

1) Determine service and country aircraft accident and ejection data requirements (injuries, equipment failure, etc...). Focus on determining what injury and injury mechanism data are required by service and by country and determine what data are not universally acquired, or not acquired at all, but deemed essential.
2) Acquire crash and survivability data on non aircraft accidents. Focus on general data, automobile crash data and correlation of measurements in anthropometric dummies to injury risk (predictive modelling of human tolerance levels), crashworthiness of vehicles and equipment and survivability of accidents, that may be useful in determination of injury mechanisms, survivability and development of crashworthiness design criteria.
3) Determine what appropriate injury criteria are available and how those criteria can be measured and analysed during testing of aircraft personnel.
4) Provide recommendations on effective accident investigation techniques and methodologies for obtaining accurate and sufficient injury data from aircraft crashes and ejection. Recommendations should enhance ability to determine injury mechanism from aircraft accidents and to prevent injuries.

This LS, sponsored by the Human Factor and Medicine Panel has been implemented by the Consultant and Exchange Programme. Thanks for the collaboration and magnificent support given for the Spanish authorities in providing the necessary facilities in Madrid to conduct this Lecture Series, and LS speakers for providing the related academic technical and scientific information.

Les aspects pathologiques et la biodynamique associée dans les enquêtes sur les accidents d'aéronefs

(RTO-EN-HFM-113)

Synthèse

La Commission RTO sur les facteurs humains et la médecine a organisé le LS-113 sur « Les aspects pathologiques et la biodynamique associée dans les enquêtes sur les accidents d'aéronefs » pour faire le point sur l'état actuel des connaissances dans ce domaine, ainsi que pour trouver de futures voies de développement pour la conception d'aéronefs résistant à l'écrasement et pour l'élaboration de critères efficaces de conception. Il s'agissait de définir les interfaces entre ce nouveau type de conception et certains aspects décisifs des enquêtes sur les accidents d'aéronefs, en particulier en ce qui concerne la médecine légale, la biodynamique des lésions, les mécanismes et l'atténuation des lésions et les implications pour la sécurité en vol de n'importe quel type de plate-forme aérienne.

Ces cycles de conférences seront axés sur la détermination des données relatives aux blessures et aux mécanismes de blessure qui seraient à rechercher au cours des enquêtes sur les accidents d'aéronefs. Des recommandations seront faites sur les techniques et méthodologies efficaces à mettre en œuvre lors de ces enquêtes.

La conférence avait pour objectif d'examiner les aspects critiques exposés plus haut, afin de :

1) Déterminer les besoins en matière de données nationales et militaires sur les accidents et les éjections (blessures, défaillances de matériel, etc...). Déterminer quelles sont les données sur les blessures et sur les mécanismes de blessure demandées par chacune des forces armées et par chacun des pays membres. Définir quelles sont les données qui ne sont pas demandées unilatéralement. Identifier les données qui ne sont pas collectées du tout, mais qui sont considérées comme étant essentielles.
2) Acquérir des données sur les collisions et la capacité de survie dans le cas d'accidents autres que des accidents d'aéronefs. Mettre l'accent sur les données à caractère général, les données des accidents d'automobiles, la corrélation entre les résultats fournis par des mannequins anthropomorphiques et les risques de blessures (la modélisation prédictive des risques par rapport aux niveaux de tolérance humaine), la résistance à l'impact des véhicules et des équipements et la capacité de survie des personnes, puisque ces éléments pourraient permettre de déterminer les mécanismes de blessure et la capacité de survie, ainsi que de développer des critères de conception résistant à l'écrasement.
3) Vérifier l'existence de critères de blessure appropriés et proposer des méthodes pour le contrôle et l'analyse de ces critères dans le cadre d'essais effectués sur le personnel navigant.
4) Fournir des recommandations sur des techniques et des méthodologies efficaces pour les enquêtes sur les accidents d'aéronefs, permettant d'obtenir des données précises et en quantité suffisante sur les blessures subies en cas d'écrasement et d'évacuation d'un aéronef. Les recommandations devraient améliorer la capacité de déterminer les mécanismes de blessure en jeu lors d'accidents d'aéronefs et empêcher de telles blessures.

Ce cycle de conférences a été présenté dans le cadre du programme des consultants et des échanges, sous l'égide de la Commission sur les facteurs humains et la médecine. Nous tenons à remercier les autorités espagnoles pour leur collaboration, ainsi que pour la qualité des installations mises à notre disposition à Madrid. Nous remercions également les conférenciers pour les informations techniques et scientifiques de haut niveau qu'ils ont fournies.

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INTRODUCTION

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Generally speaking accidents are defined in terms of damage or injury and aviation is not away of that simple concept. According to the International Civil Aviation Organization (ICAO) aircraft accident is an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which: a person is fatally or seriously injured as a result of being in the aircraft or direct in contact with any part of the aircraft, including parts which have become detached from the aircraft or direct exposure to the blast. The aircraft sustains damage or structural failure affecting the structural strength, performance or flight characteristics or require major repair or replacement of the affected component. Also it is considered an accident if the aircraft is missing or is completely inaccessible. This is the definition, but why does it happen might be our major concern and appropriate answer the biggest challenge.

All aircraft accidents are different, but the accident investigation process it should be the same, including accumulating knowledge about the facts of the accident, analyzing the data and developing conclusions.

This Lecture Series is devoted to the medical investigation related to the pathological findings associated to the biodynamics of the impact. From that perspective, the investigational accident procedure will be capable in procuring appropriate answers which necessarily will fit in the whole body of the investigation. That information is critical in producing clues about the nature of the injuries, and key for determining causal facts related to conditions capable to lead to the accident.

This information will be focused on determining what injury and injury mechanism data are required from accident investigations in order to develop recommendations on effective methodologies to use in the conduct of an investigation.

Finally this Lecture Series has long term objectives, such to promote knowledge in this specific field, also intend to facilitate networking and interchange information and create the appropriate atmosphere for future scientific and academic activities in Aircraft accident Investigation and possibly the most important one to step on future NATO common procedures which lead to interoperability.

Paper presented at the RTO HFM Lecture Series on "Pathological Aspects and Associated Biodynamics in Aircraft Accident Investigation", held in Madrid, Spain, 28-29 October 2004; Königsbrück, Germany, 2-3 November 2004, and published in RTO-EN-HFM-113.

General Aspects in Aircraft Accident Investigation

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INTRODUCTION

Mishap description and investigational procedures play a key role in understanding what areas failed in the accident sequence of events and provides us the correct tools to address appropiatte recomendations, in order to prevent future similar situations that leads to incidents or accidents.

Wiegman and Shappel (26) described years ago a practical and comprehensive model of human factors which can be applied to every accident. The so named HFACS or Human factors Accident Classification System model followed the causative models described by previously by Reason (17) and later by AGARD WG-23 (19). Nowdays it constitues a handy taxonomical tool to identify and determine causal facts related to active or latent conditions capable to lead to the accident.

The investigation of and aircraft accident is always a difficult task, in where a great number of factors might be involved and where sometimes part of the clues are hidden or missing (5,6). It is like an enormous puzzle where we have to engage all the pieces according to the info provided by meteo, engines, cell, avionics, forensic, human factors etc..., but we have very often a big challenge, some of the pieces of the puzzle are missing, deteriorated, bleached, burned, or even artificially misplaced, and we have to figure out , what are they and where to fit them.

From a biodynamic and impact point of view, the investigational accident proccess should target the preventive measures resulted from the detailed study of the crash forces involved and the type of injuries produced. The analysis of the patterns of injuries sustained by the aircrews are critical and any information concerning the type and nature of injuries involved in a fatal accident must be part of the investigation.

Results of autopsies reveal most of the time that blunt trauma is the primary cause of death in more than 75% of the fatal cases, followed by bony injuries of the ribs, skull and facial bones. Very often all injuries appear and head injuries results as the leading cause of death (2,10,27).

A recent paper pointed out the relevance of the investigation of injuries produced in the survivors, equally subjected to a mechanism of injury that can be easily study and theoretically reproduce in the survivor patient (11).

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A report of the factors associated with pilot fatalities in aircraft crashes in Alaska mentioned that the most frequent ones are (15):

- crashes involving postcrash fires
- flight in darkness or IFR conditions
- No restraints

A review of the aircraft accidents occurred in the Spanish Armed Forces showed that head and blunt trauma were the major causes of death, due to the decelerative forces originated during the impact.

AIRCRAFT ACCIDENT BOARD OF INQUIRY

There are a quite large variety of approaches, depending of the country, legal systems, military, civilian, number and qualification of the members, links with other bodies, etc.. These differences will play a key role in the involvement of the physician in the current investigation.

As an example the investigation board in the Spanish Military is composed by a president with the rank of Brig. General, pilot who represents and signs the reports of the board, a secretary that use to be a full Colonel and basically in charge of the administrative arrangements. There are a pilot representative of each Service plus the Civil Guard, an Aeronautical Engineer, a Physician, a Lawyer, and a Photographer.
Our experience demonstrate that the role of the lawyer in supporting us in all the interfaces with the judge and final review of the report according to legal standards has been very fruitfull and in our understanding necessary (19).

The role of the physician board member must be supported in a deep knowledge of the especialty of Aviation Medicine in order to understand the physiological and pathological factors involved and experience in the investigation itself. In that way provide assistance in the medical, physiological and psychological aspects of the human factors involved. Also can direct or advise if timeframe provided the possibility to be on time in the crash site, in aspects such survival rescue, and egress.

The physician especialist in aerospace medicine will gather data related to the medical history of the victims, dental records and eventually whatever available tool for identification purposes.

Also the physician will be able to identify potential site hazards and let be aware of bloodborne pathogens, composite material, chemicals, compressed gasses or even explosives such an unfired ejection seat or ammunition unexploted.

The physician will be the main advisor of the coroner in correlating the factors causing accident and injury with the safetry aspects of aircrafty design, restrain system , personel equipment, and existing operational and safety regulations, practices and conditions with other board members.

Also along with the technical personnel will evaluate the life support equipment and protective systems that it could be implicated in the cause of the injury.

But the main role it will be to make a thorough investigation of the fatal and non fatal injuries sustained to determine their causes and to recomend ways of preventing or minimizing future similar ocurrences.

CRASH SITE

Emergency medical care must be the first priority for the rescue team deployed to the crash site, but we should not forget that potential survivors are the most valuable witness of the accident and record of the names, relatives, police and hospitals where they have been admitted are extremely valuable. Inmediatly after, the medical investigation must start, but keeping all the safety measures around the accident site according to the instructions provided by the rescue teams, fire figthers and security forces. The site always is a hazarous place, and tyres, composites, batttery acids, oxygen equipment and compressed gases, radioactive material (Torium associated to FLIR), ammunition, explosives (ejection seat), weaponery, unknown load and biological tissues and fluids from the victims, are some of the potential hazards for the investigation team (18).

ICAO provides especific recommendations regarding prevention and custody of the remains that should be left as undisturbed as possible in order to preserve the information to the investigators. It is recommended that rescue workers during the access procedures to the victims and survivors do make as little damage as possible to the cabin remains or even record the ultimate stage of the cabin and position of the victims before removal and loss of information due to the on site work. Position of the switches and instruments are important and never must be remove or alter. Also the fracture surfaces of broken parts should be kept in the laying position until expertise analysis and adequate record (photography or video) is finalized.

Major components (engines, ejection seats, hydraulic partss, cabin displays) should not be dismantled in the field without direction of appropiate engineer expert, preferebly the engineer member of the board.

During aircraft recovery effort where human fragmentation occurred, especific authorization of the judge (different procedures can be applied country by country) it should be necessary for the coroner to manage the disposition of the human remains that may be located as wreckage is moved. Close collaboration with the coroner is particuraly necessary.

Special attention must be paid to the life support equipment involved such flight clothing and protective garments, smoke hoods, oxygen delivery systems, helmet and mask, G-protection suit and appropiate restrain systems.

In the case of a mass casualty situation preliminary evaluation of the location and nature of the disaster, number of casualties and availability of resources should be performed in conjunction to careful documentation of injury patterns and accurate identification of data that can be associated to the victim, plus biological sampling for further positive identification procedures.

COLLECTION OF DATA

Collection of evidence are paramount and actually the AGARD AR-361, discussed the directions and procedures used by various NATO countries in order to collect and interchange data coming from the investigation in order to reach a potential common file. In that way a human factors approach were depicted and a new approach described in order to identify failures or conditions that precede active failures. Later on, Shappel and Weigman established a system to understand why the mishap occurred and how it might be prevented from happening again in the future. A version of the domino theory of the Reason model where published describing the levels at which active failures and latent/conditions may occur within complex flight operations (19,26).

A major adjucnt in the collection of data and further positioning of the remains are the diagraming of the wreckage, by using either polar, tear drops aand grids diagrams. Each one is ideally suited for high vertical velocity of impact, scatter pattern along the main flight path vector or a more widely dispersed pattern, respectively.

Extensive on site photography play a key role in documenting and record pieces, victims position, instruments, life support equipment and other portions of the aircraft deemed important for the investigation.
Aerial photography is a great adjunct to the identification and accurate positioning of the elements of the aircraft and a major help to detailed reconstuction of the diagrams.

Information collected and examination of damage should be used for appropiate adquisition of key accident information such, angle of impact, airspeed at impact, attitude at impact, evidence of inflight fire, evidence of ground fire, in-flight structural failure, aircraft configuration and integrity of impact, whether the power plant was producing thrust, if and when ejection or bailout was attempted, phase of flight at impact (recovery, stall, spin, inverted..), evidence of mid-air collision, evidence of fuselage or cockpit intrusion and evidence of inflight incapacitation (1,3,4).

MEDICAL INVESTIGATION

The physician investigator will be in charge not only of the in site investigation but the so called off-site investigation related to the human factors involved. It will be required to interview survivors, witnesses or other individuals who might have been connected professionally to the mishap.

In addition to that the medical investigator will be responsible for determining if illness, sudden or subtlte incapacitation or medication were causal or contributing factor (22).

The medical investigation includes a full review of the crew members medical records and full professional records, including up to date physiological training (altitude physiology, night vision training, spatial orientation and centrifuge training) (9).

Medical exams of the aircrew survivors can add a valuable information regarding their physical status and a battery of test might be considered in order to rule out the event of intoxication (CO poisoning), or being under the influence of sustance intake (cocaine, alcohol, marijuana, amphetamines, opiates and medication), or simply rule out a medical problem (hypoglicemia, anemia, infection) (8,12,14).

Appropiate X-Ray exam should be orderer in the case of trauma. If ejection or bail-out, compression fractures of the spine can be expected and MR and Isotopic studies should be considered. In the event of head trauma full neorological exam must be performed along with the appropiate radiological exam and rule out parenquimatous, epidural or subdural bleeding.

Victims must be identify and appropiate methods for positive identification of them should be used such, dental records comparation, finger and footprints data, presence of previous fractures already recorded and DNA profiles. Presumtive identification are based in techniques such visual apperance, anthropometrics, personal effects, flight manifest, sex , race , age and personal items. Presumtive identification must be consider not always reliable and causiously considered (7,16,18).

Postmortem studies should answered several questions such determination of the cause and manner of death, by establishing the circumstances of the accident. Basic questions such, who is the casualty, what are the injuries, when did these injuries or conditions occur, how did occur, who caused it, where did happen and why did happen (2).

Injury patterns has to be analyzed in relation to the eventual position of the victim in the aircraft. Exam of hands, arms, feet might reflect the character of the control (stick, pedals), and actually colinear fractures of the metacarpals or metatarsals, fractures of the wrist, or distal fractures of the radius and ulna may indicate that the individual was attemting to control the aircraft at the time of the impact (20,23).

Full body X-Ray exams both with equipment and undressed provide important visual documentation mostly in high speed ejection injuries resulting in potential fatal neck or flail injuries. Radiographic exams provide the best evidence and characterization of fractures, dislocations and presence of foreign material (7).

The information collected and subsequent analysis of the data comes not only from the medical sources but from the mishap site, survivors interviews, laboratory results, radiological findings, autopsy outcome, and other sources. All of them must be pieced together in an organized way to produce the proper information, which becomes evidence that is utilized to identify the many causal factors present in the accident (1, 7,13,18,23).

The pattern of injuries sustained at impact might provide an indication or clue of what the subject was performing in such critical moment and subsequent reconstruction of the accident pattern is facilitated.

IMPACT TOLERANCE .

Analysis of crash or impact forces can be very important in determining causes of injury or death. Crash survivability focuses on what happened and why the mishap occurred, but the ultimate goal is to determine the primary cause and adjuvant circumstances in order to prevent similar events (20).

Many accident investigators have reported that 70% to 80% of all deaths and injuries in crash decelerations are from face and /or head injuries cused by body flailing and head striking surrounding structures. Survival of an aircraft accident depends to a great extent on providing a crash-resistant container for the ocupants, that is, occupiable area that will withstand crash forces without crushing, collapsing, or desintegrating, and features such as the deformation of aircraft cockpit and cabin structures, the state of integrity and probable function of seats and restarint systems, probable impact of ocupants against aircraft structures and the correlation of injuries with the direction and severity of impacts. But surviving an aircraft generally involves also tolerable deceleration forces and a non-lethal post-crash environment (1,20).

Factors affecting crash survivability has been clasically classified (1,7,18,20,23) in 5 key aspects:

1. Container related factors.

It is the capability of the airframe to maintain an intact shell around the ocupants and preserve an adequate volume of living space and prevent penetration of external or internal objects.

2. Restrain systems factors.

It is the linking of the occupants to the container in order to secure them avoiding the posibility of striking through the closest estructures of the airframe. Bassically consist of seat belt, shoulder harnesses, seat belt anchorages, and the floor used to prevent the occupants. We should consider the restarint of the cargo and components from being trown loose within the aircraft. Any failure of those systems increase the chance of injury.

3. Environmental factors.

Related to the shape and configuration of potential striking structures within the aircraft. The presence of injurious surfaces that can be avoied and replaced by energy absorbing materials wherever possible. The mishap environment might affect the ability to withstand crash forces or prevent the egress from the aircraft or combustion of products from postcrash fire. In addition self protection can be improved by the use of appropiate clothing garments, adequate underwear, socks, boots, gloves and helmet. The extensive use either for fix wing aircraft or rotary of Night Vision Devices attached to the helmet or even integrated in the helmet is an element of concern due to the added weight and hence deceleration supported.

4. Energy absortion capabilities.

It is the capability of the airframe to absorb the crash-force energy. The dynamic responses of the estructure of the aircraft during the crash impact determine how forces acting on the aircraft are trasmitted to the occupants. Desirable structures are those that absorb energy, such energy absorbing seats that progressively collapse, and absorbe impact energy at levels within the human tolerance ranges, without storing it to later produce a delayed dynamic overshoot.

5. Postcrash factors

Mainly related to fire and fumes or escape from a ditching aircraft. The control of post-crash is primarily related to aircraft design. Factors that increase the survivavility are the location of fuel cells and fuel lines in relation to electrical and mechanical ignition sources and the resistance of the fuel system components to rupture under conditions of moderate crash forces or airframe distorsion, sufficient emergency exits, breakaway valves applied to fuel lines, wear addequate clothing (cotton, nomex) and avoid synthetics in seats and cushions.

INJURY ANALYSIS

Any injuries found in the occupants must be correlated with the circumstances of the accident. All the information provided will be extremely valuable for potential future recommendations. The analysis of injuries sustained by any aircrew or passengers should intend to examine the nature of the injuries and establish the precise pathogenic mechanism which lead to identifying the cause of the accident. This effort will provide the aircraft with improved aircrew restraint, inertia reels, airbags systems, crashworthy seats, improved egress training and improved egress procedures, which will provide the aircrew and passengers with a level of protection commesurate with the risk of operating aircraft in the military and civilian environment (20,21,25).

The information provided should answered several questions related, such when the injury occur, what was the nature of the forces involved, if the injuries were as a result of the mishap forces or due to post-crash artifacts and if the injuries preexits or occur before or after death.

Injury can be the result of a direct impact against a solid object or indirectly transmitted force, resulting in damage to the bones or soft tissues and internal organs of the body.

Impact injury typically refers to structural disruption of biological tissue as a result of a short duration physical force. The duration associated with impact it is considered less than two seconds.

Sustained injury is associated to a sustained component. Tissues can be stressed in different ways, such compression stress, tension or distraction stress or combination of both compression-tension stress. Another factor to consider is the cross sectional area where it is applied, so that compression-tension stress can be defined by the force per unit area over which it is applied.

The physical basis of injury is associated to strain or degree of deformation produced by stress. The resistance to strain is defined as stiffness or resistance to deform. The strain is measured by the amount of decrease in the dimension divided by the initial value.

We can consider:
- Bending: distorts tissue about cross-axis.
- Torsion: angular distorsionabout the long axis.
- Shear: as a consequence of the structure’slip.

Any part of the body can be subjected to impact and subsequent injury, but depending of the anatomical characteristics of the human structure, composition, mass, elasticity and vital organs affected we can review several patterns associated to body organs, systems and structures (4, 20).

Skeletal injury.

Injuries afecting the limbs are very comon, even if appropiate restraint systems are used, taking into account that arms and lower extremities are not currently restrained. We can classifed according to the particular shape, location and response to an applied force or load.
- Long bones: with tubular structure, capable to absorb energy but subjected to injury mechanisms such spiral or bending fractures.

- Short bones: short and cuboidal bones such carpus and tarsus are subjected to multidirectional motion when under stress. Sometimes fractures are associated to aircraft control gear.
- Flat bones: generally they have a high resistence to deform, they broke under direct impact.
- Irregular bones: such bones of the face, can be afected by multiple forces, generally associated to direct impact against the panel.
- Spine and vertebrae: impact are more frequently associated to bending and longitudinal axis load.

Joints.

Disruption of the joint can lead to dislocation of the attached estructures and unestability of the joint. Forces applied to the joint can produce the distension or rupture of the capsule, ligaments, tendons, sweling and haemorrage.

Abdominal cavity.

The abdominal cavity reacts to an impact as a fluid–filled or hydraulic cavity in which force is wave-transmitted to all organs and structures. Most frequent type of injury is blunt trauma as a result of pressure wave transmission, compression and shear forces.

Chest.

Injury to almost any one structure of the chest can seriously compromise the survivability of the victim. Time and magnitude of the impacting force are critical for the thoracic content. Disruption of the circulatory system including aorta rupture or penetrating injuries use to be fatal.

Head and Face.

Most frequent cause of death in aircraft accidents. Open or close head injuries does not mean higher or lower rate of mortality unless it is associated to brain injury. In addition to that, very often are associated to various injuries in the rest of the body complicated with haemorrhage and lost of circulating volume.

Can be classified in:
- Contact injuries. Required a blow to the head. Direct impact can lead to skull fracture, extradural haematoma or coup contusion. Transmision can produce deformations distant from the site of the impact and result in vault and basilar fractures. Injury wave can be transmitted across and produce contracoup contusion and/or intracerebral bleeding.
- Non contact injuries. Consequence of acceleration but does not need necessarily that the head strike against any object or the head be struck by any unrestrained object. Generally associated to angular accelerations which lead to deformation of the tissue as a result of an external loading force. Surface strains can lead to subdural haematoma or contracoup contusion. Deep strains might lead to concussional syndromes and difuse axonal injury.

Spine.

Response might be different from individual to individual, according to the age, physical fitness, posture (mainly in ejections), and involvement of the musculo-skeletal support of the vertebral column and spinal cord. The motion of the spine is complex and associated to coupled motions, i.e. lateral bending involves rotation about the horizontal and vertical axes as well as the translation perpendicular to the horizontal plane, hence lateral bending may cause a combination of transverse shear in the horizontal plane, rotational shear about the vertical axis and tensile and compressive stresses in the vertebral body. Other mechanisms are associated to hyperextension, hyperflexion with or without compression (7, 20).

Tolerance is not uniform along the spine. Association with stability is key for determining irreversible complications such quadriplegia or paraplegia.

Injuries associated to assisted scape from aircraft are more frequent in the thoraco lumbar hinge (T12-L1), although a significant proportion of injuries also occur at the mid-thoracic level. The combination of axial compressive force and spinal flexion lead to the most frequent one, the anterior wedge fractures. From an anatomical point of view can be classified in (24):

- Anterior wedge fractures.
- Burst fractures.
- Chance fractures.
- Dislocations and fracture-dislocations.
- Rotational injuries.
- Hyperextension injuries.

Injuries also can be classified in four major groups according to the mechanism of production (7):

- Intrusive injuries: Due to loss of occupiable space as a result of the intrusion of portions of the aircraft and /or surrounding objects, such trees, wires, poles etc.. most frequently generates the so called “crush injuries”.
- Thermal injuries: Associated to postcrash fires. It is very relevant to distinguish if fire started during flight or after impact and if the resulting thermal injuries were the cause of death or merely an artifact sustained after death. During autopsy procedures it is critical to look for presence of soot in the trachea and rest of the airways. It is rather common to find in bodies exposed to fire artifactual situations not necessarily associated to the cause of death such, pugilistic attitude of extremities, thermal fractures of long bones and skull, epidural haematomas and splitting of soft tissue.
- Impact: The classically described as control surface injuries are non specific and can be seen not only in pilots but even in the passengers, therefore their interpretation must be cautious. Most frequent control injuries are described in hands, carpal, metacarpal, tarsal, and metatarsal bones, associated to lacerations in the palms and soles.
- Decelerative forces: depends on both magnitude and duration force. Experimental human tolerance estimates for 0.1 sec. Decelerations described bellow derived from laboratories and artificial crash-impact research (modified from Naval Flight Surgeon Manual, Pocket Reference to Aircraft Accident Mishap).

Pulmonary contusion	25 G
Nose fracture	30 G
Vertebral body compression	20-30 G
Fracture dislocation of C1-C2	20-40 G
Mandible fracture	40 G
Maxilla fracture	50 G
Aorta intimal tear	50 G
Aorta transection	80-100 G
Pelvic fracture	100-200 G
Vertebral body transection	200-300 G
Total body fragmentation	350 G
Concussion over 0.02 sec.	60 G
Concussion over 0.005 sec.	100 G
Concussion over 0.002 sec.	180 G

RECOMMENDATIONS AND PREVENTION

Direct consequences of the investigation should lead to specific changes that may improve crashworthiness of the respective aircraft an in addition, significant operational lessons were drawn and which, by application learnt, led to greater safety.

Tolerance levels demonstrated by dummies studies can show the effectiveness of the various configurations of restrait systems and resistance of the airframe to deformity and capability to crush.

The documentation and the pathological interpretation of the injuries associated to the aircraft accident determined how they occurred, a key premise in order to establish conclusions and be able to minimize or prevent future similar events.

Data collection and interoperability procedures must be stablished by developping the actual framework provided by STANAG 3531.

BIBLIOGRAPHY

1. Antuñano M, Banks R, Bellenkes A, Cohen M, Fraser J, Garber M, Hansrote R, King R, Neubauer J, Rayman R, Ruehle C, Sahiar F, Veroneau S, Wagner G. Primer on Aircraft Accident Investigation for the Aerospace Medicine Investigator. Aerospace Medical Association, Alexandria, 2000.

2. Ast FW et al. Fatal aviation accidents in Lower Saxony from 1979-1996. Forensic Science International. 119: 68-71, 2001.

3. Baker SP, Lamb MW, Li G, Dodd RS. Crashes of instructional flights. Aviat Space and Environ Med., 67: 105-10, 1996.

4. Battista V and Schwegmann J. Review of injuries in a UH-60 midair collision. Military Medicine, 164: 656-7, 1999.

5. Braithwaite MG et al. The hazard of spatial disorientation during helicopter flight using night vision devices. Aviat Space and Environment Med, 69: 1038-44, 1998.

6. Braithwaite MG et al. Spatial disorientation in US Army rotary wing operations. Aviat Space and Environment Med, 69: 1031-7, 1998.

7. Bellenkes A, Trenholm B, Jones N, Vallaster B, Fraser J, Knittel D, Webster N. The Naval Flight Surgeons Pocket Reference Aircraft Mishap Investigation. 5th Edition, Norfolk, 2001.

8. Chaturvedi AK, Smith DR, Canfield DV. Blood CO and HC concentrations in the fatalities of fire and non-fire associated civil aviation accidents. Forensic Science International. 121: 183-8, 2001.

9. Cullen SA, Drysdale HC, Mayes RW. Role of medical factors in 1000 fatal aviation accident: case note study. BMJ, 314: 1952, 1997.

10. De Lorenzo RA, Freid RL and Villarin AR. Army aeromedical crash rates. Military Medicine, 164: 116-8, 1999.

11. Friedman A et al. Light aircraft crash- a case analysis of injuries. Isr Med Assoc J. 4: 337-9, 2002.

12. Irvine D and Davies DM. British Airways flightdeck mortality study 1950-1992. Aviat Space & Environ Med, 70: 548-555, 1999.

13. Knapp CJ and Jonhson R. F-16 Class A mishaps in the US Air Force. Aviat Space and Environment med. 67: 777-83, 1996.

14. Li G, Hooten EG, Baker SP, Butts JD. Alcohol in aviation related fatalities: North Carolina 1985-1994. Aviat Space and Environmen Med, 69: 755-60, 1998.

15. MMWR report. Factors associated with pilot fatalities in work related aircraft crashes-Alaska, 1990-1999. MMWR, 220, 51:407.

16. Newhill CE and Sites EW. Identifying human remains following an air disaster:the role of social work. Social work in Health Care. 31: 85-105, 2000.

17. Reason J. Human Error. Cambridge University Press, 1st Ed., 1994.

18. Rios F. Manual para la Investigacion Medica de Accidentes Aereos. Ed. Ministerio de Defensa, Madrid, 1999.

19. Rios F, Magnusson K, Cugley J, Courchesme C, Alnaes E, Knoefel J, Grau JY, Lyons T, Guadalupi F. The prevention of aircraft accidents through the collection and analysis of human factor/aeromedical aircraft accident data. AGARD-AR-361. Paris, AGARD, 1998.

20. Rios F, Cugley J, Raddin JH, Banks RD, Cogswell SC and Hepper A. Injury prevention in aircraft crashes: investigative techniques and applications. AGARD-LS-208. Paris, AGARD, 1998.

21. Shatz DV. Critical analysis of injuries sustained in the TWA Flight 800 midair disaster. J. Trauma-Injury Infection & Critical Care. 48: 987-8, 2000.

22. STANAG 3531. Aircraft Accident Investigation. NATO. Brussels, 1998.

23. The Society of United States Air Force Flight Surgeons, Aircraft Mishap Investigation Handbook, 1st Ed, San Antonio, TX, 1994.

24. Vieyra H. And Anton D. Orthopedics. In Aviation Medicine. J. Ernsting and P. King, Butterworths, London 1988.

25. Vosswinkel JA et al. Critical analysis of injuries sustained in the TWA Flight 800 midair disaster. J. Trauma. 47-617-621, 1999.

26. Wiegmann DA and Shappel S A. Human error and crew resource management failures in Naval Aviation mishaps: A review of US naval Safety center data, 1990-96. Aviat, Space , Environ Med, 70: 1147-51, 1999.

27. Wiegmann DA and Taneja N. Analysis of injuries among pilots involved in fatal general aviation airplane accidents. Accident Analysis & Prevention. 35: 571-7, 2003.

Accident Investigation Techniques and Methodologies

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Injuries in Fatal Aircraft Accidents

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Mechanisms of Injury in Aircraft Accidents

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

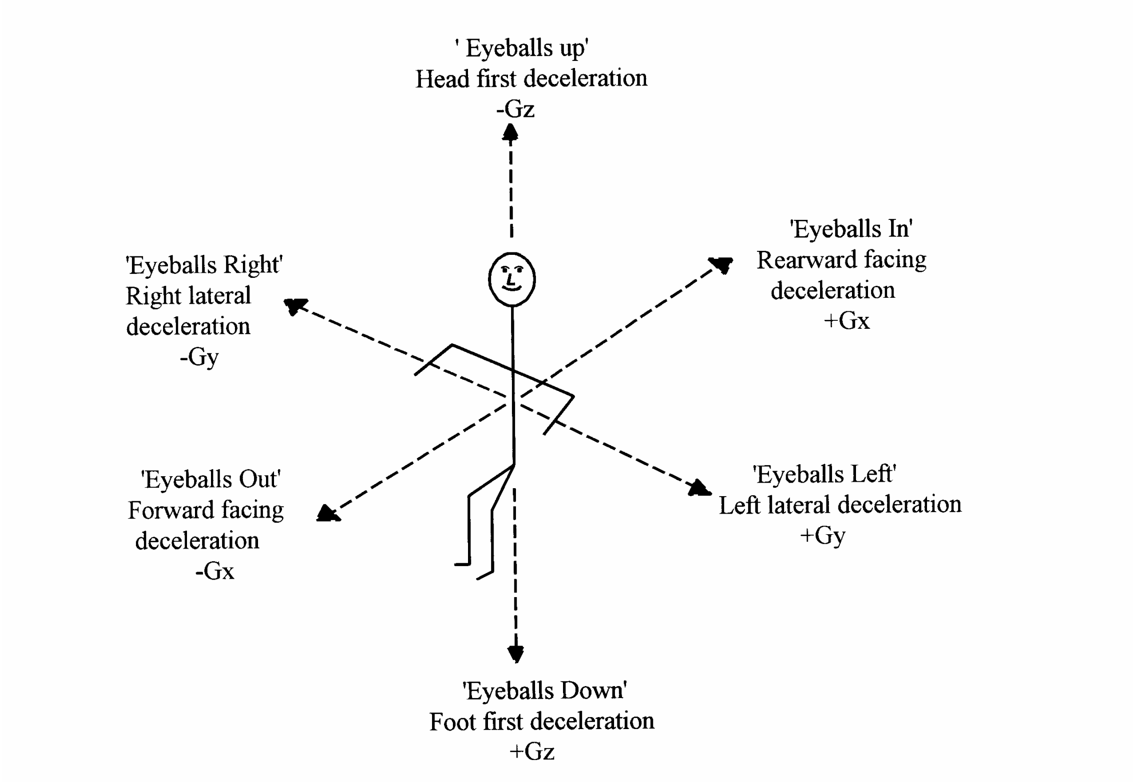

Figure 1. The effects of deceleration. The standard aeromedical terminology for describing the forces. The vector arrows indicate the direction of the resultant inertial forces.

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

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

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

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

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

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

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

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

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

Table 1. Injury and deceleration needed

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

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

Injury Analysis and Scoring Systems

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

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

Table 2. Injury Scoring System (Hill 1987)

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

Some Specific Injuries

Head Injury

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

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

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

Spinal Injury

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

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

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

Thoracic Injury

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

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

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

Abdominal Injury

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

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

Limb Injuries

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

Patterns of Injury and their role in Accident Reconstruction

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

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

Case 1

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

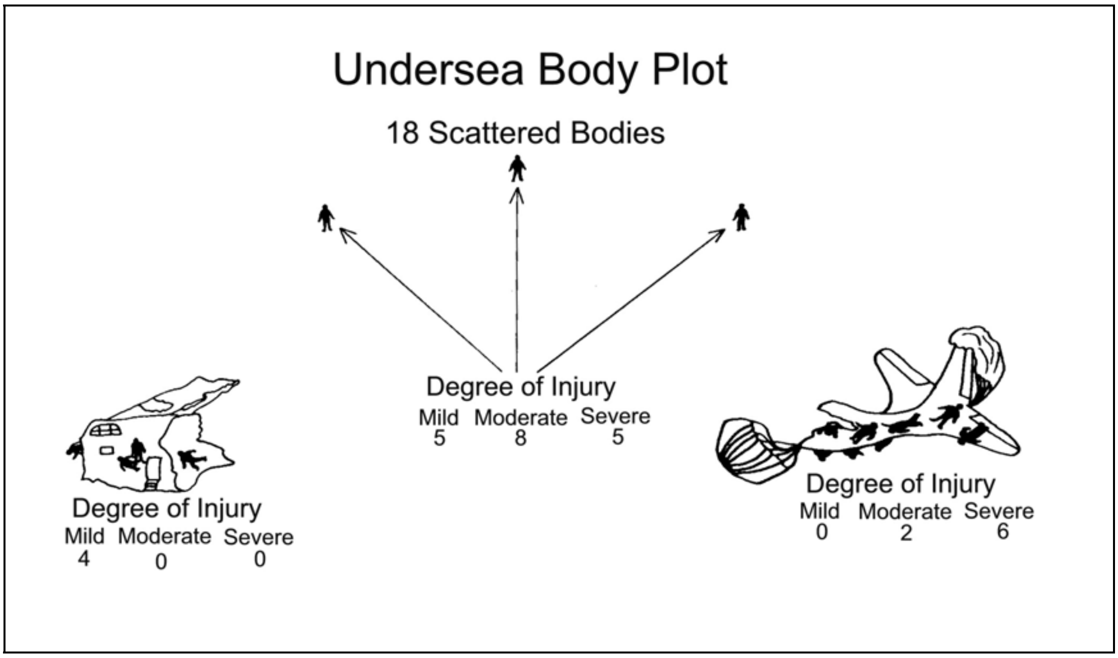

Figure 2. Plot relating injury to recovery position.

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

Case 2

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

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

Table 3. Fatal Injuries sustained in Case 2

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

Table 4. Leg fractures in Case 2

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

Table 5. Jack-knifing injuries in Case 2

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

Case 3

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

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

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

Case 4

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

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

Case 5

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

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

Patterns of Injury in Comparative Accident Investigation

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

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

Table 6. Comparison of injuries sustained in two accidents

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

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

Table 7. Two clearly dissimilar accidents over the sea

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

Recurring Injury Patterns

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

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

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

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

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

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

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

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

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

The pilot's position

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

The mechanism of injury

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

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

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

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

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

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

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

Examination of clothing

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

References

Anton. D.J. 1988: Crash dynamics and restraint systems. In Ernsting. J. and King. P. (Eds.) *Aviation medicine.* London. Butterworths. 168-169.

Armstrong. J.A. Fryer. D.I. Stewart. W.K. Whittingham, H.E. 1955: *Interpretation of injuries in the Comet aircraft disasters.* Lancet. i.1135-1144.

Baker, S.P., O'Neill, B. Haddon, W. et al. 1974: *The injury severity score; A method for describing patients with multiple injuries and evaluating trauma care.* Journal Of Trauma. 14. 187-196.

Bull, J.P. 1975. *The injury severity score of road traffic casualties in relation to mortality, time of death, hospital, treatment and disability.* Accident Analysis and Prevention. 7.249-255

Clancey, V.J. 1968. *Comet G-ARCO: Solving the riddle.* New Scientist. 37. 533-537.

Cullen. S.A. 1973: Death in general aviation accidents and its prevention. In: Reals. W.J. and Mason. J.K. (Eds.) *Aerospace Pathology,* College of American Pathologists. Chicago. 105-113.

Cullen. S.A. and Turk. E.P. 1980: *The value of postmortem examination of passengers in fatal aviation accidents.* Aviation, Space and Environmental Medicine.51.1071-1073.

Cugley, J. and Glaister, D.H. 1999. Short duration acceleration. In Ernsting. J., Nicholson, A.J. and Rainford, D.J. (Eds). *Aviation Medicine, 3^{rd} Ed.* Butterworth-Heinemann. Oxford. 157-166.

Hill. I.R. 1987: The Air India jumbo jet disaster Kalishna - injury analysis. In Caddy. B. (Ed.). *Uses of forensic sciences.* Edinburgh. Scottish Academic Press. 120-145.

Krefft. S. 1970: *Who was at the aircraft's controls when the fatal accident occurred?* Aerospace Medicine. 41. 785-789.

Mason. J.K. 1970: *Passenger tie-down failure: Injuries and accident reconstruction.* Aerospace Medicine. 41.781-785.

Mason. J.K. 1973: *Injuries sustained in fatal aircraft accidents.* British Journal of Hospital Medicine. 9.645.

Mason. J.K. Tarlton. S.W. 1969: *The medical investigation of the loss of the Comet 4B aircraft 1967.* Lancet. i.431-434.

Simson, L.R. 1971: *"Chin-Sternum-Heart Syndrome": Cardiac injury associated with parachuting mishaps.* Aerospace Medicine.42. 1214-1217.

White, B.D., Firth, J.L., Rowles, J.M. and NLDB Study Group. 1993. *The effects of structural failure on injuries sustained in the M1 Boeing 737/400 disaster, January 1989.* Aviation, Space and Environmental Medicine. 64: 95-102.

Young, J.W. 1966: *Recommendations for restraint installation in general aviation aircraft.* Report AM 66-33 Federal Aviation Agency, Oklahoma City, Oklahoma.

Investigation of In-Flight Medical Incapacitations and Impairments

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Toxicological and Pathological Findings

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SUMMARY

When investigating a fatal aircraft accident, the medical experts must also consider the requirements of the local public prosecution. The peculiarities in the toxicological and histological examination result on the one hand from the complexity of the matter and on the other hand from the elevated demands of conclusiveness and the variety of the examinations to be performed. The answering of the relevant questions regarding the aircraft accident investigation in connection with the critical assessment and interpretation of the findings makes highest demands on the investigators. The specific aspects and pitfalls regarding the assessment of the postmortal alcohol detection, the diagnostics of chronic alcohol abuse, the analysis of POL substances and combustion gases, the diagnostics of disturbances of the glucose metabolism and the microscopic examination of the heart will be discussed.

1 INTRODUCTION

According to STANAG 3318, aircraft accident investigation must enable answering the question whether the fitness for flying duty of the crew members was hampered by alcohol, medication, drugs, or other toxic substances such as POL (inhalation of hydraulic oil, kerosene etc.) incineration or exhaust gases and the thermal decomposition products of organic material. Moreover, the possibility of pathological changes having affected the airworthiness of crew members must be investigated and if such changes are due to acute or latent diseases.

Since the public prosecution of the various nations is the competent authority for the investigation of cases of unnatural death attending to the question of responsibility, any case requires the cooperation of the Federal Ministry of Defense with the respective German local prosecutor. Therefore, basic criteria for the liability of the methods of investigation must be observed.

Several peculiarities of the toxicological investigation procedures which are applied for aircraft accident investigation and several aspects of postmortal biochemical methods will be discussed in the following, possibly in conjunction with pathological findings.

2 CONSIDERATION OF THE MATERIAL TO BE INVESTIGATED AND THE NECESSARY SYMBIOSIS OF PATHOLOGIST AND TOXICOLOGIST:

The members of the aircraft accident crash group take samples for analysis at the site of the accident or in the mortuaries where the autopsy is carried out. Then the samples are transferred refrigerated or frozen to

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the precincts of the Division Aircraft Accident Investigation to be analyzed. According to the principle "chain of custody", registration, receipt, treatment, and transfer of the material to the individual specialists, places where samples are kept, different phases of analysis are all recorded. This complete documentation enables to find out at any time who handled the material at what time and where. So, falsifications, confusions or willful manipulations can be excluded. If this documentation is missing, it cannot be re-enacted, if any substances and their concentrations which are detected at a later stage were at all relevant rendering impossible any final objective interpretation. If such conditions are not complied with, no disciplinary or criminal consequences can be drawn. The pathologists who know the conditions of the crash site and the particular conditions of the bodies - determine - together with the toxicologist - the choice of the samples and their treatment, the extractions, and the examination techniques. They have to consider the evidential value of the method applied and its specificity and accuracy. As a rule, blood, urine, hairs, tissue samples of the brain, heart, liver, kidneys, fatty tissues, etc. are tested for alcohol, medications and drugs. Not only the qualities of the specific substances, or the catabolic decomposition products are determined by two independently applied methods, but also their individual quantities are identified by two different analysts. As a rule, the quantitative result is the total of the results of several individual tests. Then an average value is calculated. According to the pertinent regulations, the individual results cannot but very slightly deviate from the stipulated figures. Legal authorization for the performance of such tests is only granted on condition that laboratories perform a successful external round robin test. They will receive a certificate which will be valid for a short time period, namely a couple of months. Such certificates warrant technical expertise to analyze certain substances such as medication, drugs, alcohol, and others; other certificates are granted for expertise in dealing with materials such as hairs, blood, urine etc.

This shows that quality assurance of the forensic-toxicological analyses which are performed on the occasion of an aircraft accident, is considered to be extremely relevant; Therefore it is indispensable to perform careful quality control.

Before the actual analyses are carried out, the pathologist who is responsible for the autopsy and takes the samples, and the toxicologist need to discuss the appropriate way of proceeding the samples. So, the pathologist will separate a piece from a central part of a muscle and change the scalpel frequently to provide uncontaminated material for investigation by the analyst. Contamination can be caused by POL, such as lubricants, Avgas or other chemical substances or pollution which can have affected the corpse at the crash site and which can interfere with the analysis of the materials. Moreover, continuous feedback is required during the course of analyses in order to enable the discussion of first test results so that their relevance can be evaluated in the individual case, even in the face of new questions and further examination methods to be applied. On the other side, feedback from the laboratory can trigger improvements in the sampling method, or call for taking necessary samples of different material.

3 FOCI OF EFFORTS IN TOXICOLOGY AND PATHOLOGY

3.1 Alcohol

The identification of alcohol in serum, blood, or urine samples taken from living probands is unproblematic, even after storage in the refrigerator at 4° C temperature for several months. The concentrations of congener alcohol in beverages can just as well be differentiated regarding type and quantities of alcohol consumption (wine, beer, spirits, etc.), even if the person involved alleges to have consumed massive portions of alcohol posterior to the accident.

However, examination of aircraft accident victims can be a difficult task when corpses are heavily disintegrated or were exposed to excessive heat of the sun or of flames; sometimes autolysis and putrefaction have set in or the remains are contaminated by POL substances or extraneous matter. The laboratory tests aim at determining blood alcohol concentrations which prevailed at the moment of the crash.

When blood could be taken during the autopsy, it must have been properly extracted from the femoral vein, since it is located far enough from the stomach to exclude potential false results which could be caused by postmortal diffusion processes. Alterations of water content in the blood and in the body may be conducive to false results which should be corrected in accordance with the water content found in the test material. Simultaneous tests of congener alcohol such as propanol-1, methanol, propanol-2, butanol-1, and butanol-2, isobutanol, and 1 and 2- methylbutanol-1 etc. disclose the possibly postmortal formation of alcohol. The precondition is the evaluation and control of the presence of so-called putrefaction markers. However, if such putrefaction markers are increased, microbiological exams will be required additionally to detect the presence of bacteria and fungi. According to the type of microorganisms, very different congener alcohols can develop as metabolic products such as the above mentioned types of alcohol and amino acids. They are of decisive importance for the assessment of the blood alcohol concentration of the persons involved at the time of the accident.

In the presence of abdominal injuries, blood alcohol concentrations can be distorted, even if samples have been taken properly from the femoral vein. In such cases therefore, it is necessary to examine other tissues and liquids, such as cerebrospinal fluid, cerebral tissue, muscles from the extremities, vitreous fluid, bone marrow, lung and kidney tissue, urine, gastric contents, synovial fluid and others and to determine the water content. Aircraft accident investigation should pay special attention to hematomas for detection of alcohol, since hematomas keep the alcohol concentrations at the moment they occurred, namely at the time of the crash. The results of numerous and different materials provide for the determination of the distribution phase of ethanol (phase of resorption or of elimination). It is evident that - just as blood - all the other samples have to be tested for the existence of congener alcohols and microbiological test methods have additionally to be applied because the development of alcohol may have progressed at different speed in the various materials. In cases with severely putrefied samples usable results are often obtained from the test of the vitreous humour, because there bacterial degradation occurs only at a late stage.

3.1.1 Factors possibly affecting the blood alcohol content

Full blood is made up by corpuscular components and the blood plasma. Serum (blood plasma minus fibrinogen) has a water content of about 90%, as compared to full blood whose water content is about 80%. Alcohol concentration of the living is determined in blood serum obtained by centrifuging and the value is adjusted to full blood using the above mentioned water contents ratio. As for corpses this cannot be done. In this cases the alcohol concentration is calculated using the actual water content of cadaver blood and the average water content of full blood of 80 %.

This procedure can also be applied to the other materials to be analyzed. In analogous manner this applies to the calculation of the congener alcohols.

3.1.2 Formation of alcohol due to bacterial activity

In an environment of putrefaction, bacteria need a carbohydrate substrate like glucose to produce alcohol. Due to bacterial activities of various Proteus strains and other bacteria, blood alcohol levels up to 2 $^{o}/_{oo}$ and urine alcohol levels up to 5 $^{o}/_{oo}$ and more could be measured, depending on the respective glucose concentrations. A whole series of ubiquitous bacteria and fungi produces alcohol, such as: Escherichia coli species., Pseudomonas species, Pulularia species, Candida albicans and many more. Anaerobic and aerobic bacteria are distinguished from one another according to the different patterns of the above-mentioned congener alcohols they can produce in addition to ethyl alcohol; they differ from yeasts which as a rule do not produce such a great variety of substances. The formation of these bacterial decomposition products is controlled by temperature, pH value, concentrations of available carbohydrates and other nutritive substances. On the crash site, this problem must be accounted for when dealing with aircraft accident victims, in order to avoid any mistakes when the true causes of a crash are looked for. The detected alcohol which has been taken in with beverages cannot be distinguished from alcohol which has been produced by bacterial activity. This is another reason why a large quantity of tissue and fluid samples which are not affected by putrefactive changes, should be safeguarded to enable correct interpretation.

Experience has shown that clostridia and a variety of Proteus bacteria produce the highest concentrations of ethanol. In addition to ethanol, several amino acids are produced according to a special fermentation pattern, such as α-aminobutyric acid and γ-aminobutyric acid, or δ-amino valeric acid. One has therefore to conclude that samples of material which show criteria of microbial formation of congener alcohols and amino acids must be excluded from the start to answer the question if alcohol has affected or not fitness for flying duty.

3.2 The question of chronic alcohol abuse

Whereas, in the case of acute alcohol intoxication, histological tests do not disclose any characteristic findings, in chronic alcohol abuse histological findings in the liver are dominating. It must be taken into consideration, however, that the various findings are unspecific by itself. Only the spectrum of morphological hepatic changes together with the findings of the clinical history (which were documented during the test for aeromedical disposition) permits the assessment if alcohol abuse is really causal for hepatic damage. Large-scaled test series disclosed that approximately 20 to 30% of chronical alcoholics had normal findings in liver biopsies. Alcoholic fatty livers show in enzyme-histochemical tests patches of deficient activity of the lactate dehydrogenase including stronger NADPH-dependent reactions of aldehyde. But independently of the fatty degeneration of liver and beyond, other degenerative and inflammatory alterations due to alcohol abuse are found in the liver, such as chronical or acutely inflammatory infiltrations of the portal fields and lobules; particularly in the area of necrobioses and individual necroses where central lobular sections are preferred. The true designation would be toxic hepatosis or fatty liver hepatitis in alcoholics. (In the anglo-american environment this finding is called “acute alcoholic hepatitis”.) Hyaline deposits within the cell plasm are very characteristic, particularly when they are found in the centrolobular hepatocytes which are denominated “alcoholic hyaline” or “Mallory bodies”. These are blurred cloudy cytoplasmic solidifications close to the nucleus which manifest themselves in plump or elongated form and acidophilic consistency. The electron microscope study shows the hyaline material to consist of drop-shaped or striped assemblies of moderate electron density; under a more powerful resolution, the three layer structure of the membranes become evident together with granular portions similar to ribosomes. This alcoholic hyaline must be clearly distinguished from giant mitochondria which are rarely found. These are small homogenous clearly defined cytoplasmic inclusions in the hepatocytes, the contour of which is plump or like a cigar. The last-mentioned finding is unspecific and can be interpreted as insufficiency of the mitochondria. In general, 40 % of the cases of fatty liver hepatitis are found with Mallory bodies. In most cases, the Kupffer star cells are enlarged and increased in number and often contain deposits of iron pigment which is called in German “drinkers’ iron”. In the central lobular areas is found an increase of reticular and collagenous fibers which seem to be woven in by a net of individual or by groups of hepatocyte epithelia. This picture of “wire-netting” fibrosis together with Mallory bodies is considered to be a powerful indication for the existence of chronic liver damage caused by alcohol abuse. The chronic course of fatty liver hepatitis is manifest by an increased number of histiocytic cell infiltrations and activated star cells. Going out from the lobular center, the hepatic parenchym will fibrose and sclerose at a later stage including the intermediary and periportal areas. The resulting hepatic cirrhoses have different manifestations: they are either throughout nodose or have differently sized parenchymous patches, the so-called post-necrotic cirrhosis which is found in 10 to 20% of all alcoholics. However, this condition presupposes a 10 to 15 years’ time period of development. Pancreatic inflammations due to alcohol intake are found in combination with hepatic alterations also due to alcohol abuse in a number of cases. More than one third of the cases of chronically sclerosed pancreatitis are caused by alcoholism and this is the prototype of pancreatitis due to alcohol abuse. It is a very intensive peri- and intralobular sclerosing associated with parenchymatous atrophy and no relevant interstitial inflammatory infiltrations. Moreover, dilatations and thickened secretions are found in the glandular cavities of the acinus, ductal ectasias, epithelial flattening and pronounced parietal sclerosis of the pancreatic vessels. The islets of Langerhans often show moderate peri- and intrainsular fibroses. Lipolytic and proteolytic foci can just as well occur as inflammatory infiltrates or smaller hemorrhages.

Also the central nervous system discloses different histomorphologic findings which are caused by chronic alcohol abuse. The most important diseases initiated by alcohol include Wernicke's encephalopathy with alterations in the area of the 3rd and 4th ventricle and the cerebral aqueduct. Proliferations of the glia and particularly of the astroglia and the microglia are observed together with the vegetation of the capillaries whose walls are thickened. Seldom found and prevailing in the Mediterranean countries, where alcoholics prefer red wine, alterations of the brain are found as a pontine myelinosis or a primary degenerative disease of the cerebellar cortex preferably of the vermis and the alcoholic amblyopia which can have been preceded by visual disturbances.

Other alterations which - together with certain symptoms combinations - are indicative of the development of haemorrhageous internal pachymeningopathy extending over the frontal parts of the cerebrum and whose symptomatic is the thickening of the connective tissue of the pia mater.

Histological examination of cardiomyopathy as a consequence of chronical alcohol consumption as mentioned by clinical doctors shows - among other findings - hypertrophic and partly degenerative muscle fibers, various degrees of fibroses in the myocardium, blotchy endocardial fibro-elastoses, parietal thrombi, and inflammatory foci in the endocardium and epicardium. The electron microscopic examination proves the intumescence of the mitochondria reducing the size of the cristae. The myofibrilla reveal various changes even the complete loss of the striation and the dissolution of the myofilaments.

The histo-morphological findings just mentioned can only be considered to be a hint for a chronic alcohol abuse; however, when the laboratory parameters are evaluated and taken into account such findings become still more relevant. So, on the occasion of aircraft accidents, the records of the tests for aeromedical disposition, especially the laboratory parameters are looked into, not only for assessment of the consequences of chronical alcohol abuse, but also regarding other morphologic-pathological changes.

The medium corpuscular erythrocyte volume (MCV), gamma glutamyl transferase (GGT), the transaminases ALT and AST and their ratio, the methanol concentration, and CDT (carbo-hydrate deficient transferrin) are considered to be the typical biochemical markers for alcoholism. CDT determination has shown that commercial kits are inappropriate for assessment but it is necessary to carry out this test by high pressure liquid chromatography (HPLC). Based on a study of our pilots collective, we assume the normal value to be up to 2 % of Disialo-transferrin. The decisive advantages of the HPLC method are as follows: complete separation of the alcohol-relevant isoforms of transferrin and avoidance of false-positive results.

There are three genetic principal types B, C, and D of the iron transport protein Transferrin which again can be divided into more than 20 sub-types. The C-type prevails by 90% within the population. As far as known by now genetic variants are due to a point mutation in the DNA sequence. The result of this condition is a change of the amino acid sequence of the protein and this entails a change of biochemical qualities. According to the method of CDT determination, certain genetic constellations are likely to produce false results. So, the CDT-determination of a C/D heterozygous person will produce a false-positive result, whereas the analysis of a B/C heterozygous person will render too low values, if one of the common immunoassay methods are applied. Due to the principle of the method such false values are not even obvious. Such false results can only be avoided, if the HPLC method (possibly with iso-electric focussing) is used for CDT-determination, since the HPLC chromatogram provides for detecting the B/C or C/D variants.

3.3 On the effects of POL substances and combustion gases

Aircraft carry large quantities of fuel onboard; in addition there are deicing agents (containing frequently alcohol), lubricants, hydraulic oils, hydrazine, and other liquids. In an aircraft crash, the fuel - mostly F-34 - immediately catches fire due to its high ignitability; as a result large quantities of combustion gases develop in no time. On the one hand, such gases can be aspired by the surviving victims, on the other hand they can affect postmortal investigation considerably since they have contaminant properties. Therefore, it is sometimes very difficult to answer the question, if the fire conflagrated during flight with the consequent development of combustion gases, or if the fire broke out at the moment of the crash. Moreover, plastic material which is built in the aircraft can degrade to hydrochloric acid (HCl) and finally prussic acid (HCN) due to contamination. In the autopsies, we try to avoid such problems when the corpses are contaminated by the choice of the investigation material. So, when large quantities of fuel or other POL have poured over the corpses and have diffused through the skin due to their high fat-solubility we often change the scalpel and after removing superficial layers of the femoral muscles we take off deep muscular tissue. Suitable is also bone marrow or liquid from the larger joints. Kerosene and other contaminating substances preclude evaluation of the material by chromatography techniques; under such circumstances the questions we are interested in cannot be answered.

Contaminations, however, can be caused by other conditions which I would like to describe in the following:

During a training flight in Canada, 150 NM south-south-east of the Goose Bay airfield, a Tornado PA 200 crashed after having touched ground in a narrow valley. The crew lost their lives. Both crew members died as a consequence of polytrauma combined with craniocerebral trauma, massive thoracic and abdominal injuries associated with excessive loss of blood. According to the toxicological investigations, neither the pilot nor the weapon systems officer (WSO) had been influenced by alcohol, drugs or medication. The toxicological examination (GC-MS) of blood samples taken from the pectoral cavity of the WSO disclosed the presence of volatile substances such as intensive to very intensive signals of α-pinene and β-pinene, lemonene, and β-phellandrene, and small to very small signals of camphene, β-mycene, 2- and 3-carene and α-phellandrene.

Some herbal drugs against the common cold, such as Gelomyrtol® contain such and other similar volatile substances. The medical records of this pilot did not disclose any clue regarding the intake of such a drug. All such volatile substances however are the typical components of pine and cone oils such as of most coniferous trees. When the autopsy reports were consulted, the victim was found with several wood particles in the right upper abdomen which had penetrated him from the transitional part of the right part of the neck towards the shoulder and perforated the pectoral cavity and the diaphragm and which had thus contaminated the material to be analyzed in our laboratory. The pine needles which were safeguarded at the crash site were analyzed by gas chromatography mass spectrometry procedures proved to have the same volatile substances of comparable intensity.

If no contamination occurred, as a rule it is not difficult to prove the existence of inhaled combustion gases. F-34 fuel is a mixture of saturated hydrocarbons (alcane and cycloalcane), unsaturated hydrocarbons (alcenes and aromatous compounds) such as benzene, toluene, and naphthalene and technically caused pollution such as sulfides and disulfides, sulfurous hydrocarbons such as mercapane and nitrogenous compounds (pyridines and homologous substances). Moreover, there are additive substances which have to be considered such as icing inhibitors (ethyleneglycol monomethyl ester), corrosion inhibitors, anti-oxydant agents, agents against static charge, and substances for the improvement of flow properties. The most important component of all the other POL substances such as lubricants and hydraulic oils also contain fractions of mineral oil or synthetic oils. In the toxicological investigation practise, additive substances are relevant only regarding the identification of fuel. Pyrolysis and oxidation products which developed during the combustion of hydrocarbons are of exclusive relevance. Sometimes, the identification of carbonmonoxide proves to be difficult with degraded bodies, since the common photometric methods do not yield reliable and substantial results. Since, under deficient oxygen supply and very high combustion temperature, combustion remains incomplete, the result will be carbonmonoxide making up a very strong compound with hemoglobine or myoglobine which will have the well-known consequences.

Our Division Forensic Medicine and Aircraft Accident Investigation applies as a routine photometric procedure the measuring of nine important wavelengths. Due to the difficulties arising with photometric methods which seem to be applied in all forensic medical institutes in Germany, in addition to this photometric method we developed the analytic method of gas chromatography which is not or not more used in other institutions, because it requires excessive efforts. Gas chromatographic separation is performed on columns packed with molecular sieves or capillary columns. Detection is achieved with a flame ionization detector after reduction of CO to methane by hydrogen. Samples for analysis are muscles or the inner organs, when no blood is available due to disintegration of bodies or the bodies are found in advanced state of autolysis and putrefaction. Carbon monoxide bound to myoglobin or to the hemoglobin in organs is measured in such cases. Sometimes the determination of cyanide is problematic too. In the first place we practice gas chromatographic separation on packed or capillary columns of the volatile hydrogen cyanide and photometric detection.

Due to the normally very scarce concentrations of substances whose existence is to be proved (POL material, pyrolysis and combustion products), such substances must be concentrated and interfering matrix components must be removed from them. For this purpose, Headspace Techniques, Purge&Trap Systems, and Headspace Solid Phase microextractions are applied in the first place.

3.4 Postmortal diagnostics of disturbances of the glucose metabolism

3.4.1 Pathological findings

When the causes of an aircraft accident are investigated, the possibility of disturbances of the glucose metabolism must be taken into account. The diagnosis of diabetes mellitus or the diabetic coma are of particular relevance in an aircraft accident investigation. Apart from the findings of the internal and external inspection of the body, namely the autopsy which discloses - among other things – punctures and epidermal findings typical for diabetes like chronic ulcers or epidermatomycosis and are associated with obesity or a poor nutritional condition, the following findings are indicative for the above-mentioned condition: the stiff condition of the brain substance, xanthochromia of the cranial vault and of the subcutaneous fat tissue as well as several varieties of chronic pancreatitis and renal alterations like the Kimmelstiel-Wilson glomerulosclerosis. The following phenomena can be indicative of the presence of a diabetic coma: cerebral edema, acute terminal pancreatitis, swollen pale kidneys in the presence of glycogen nephrosis with large phytoid Armanni-Ebstein-cells in the straight areas of the proximal tubule in the lower part of the medullary rays and in the external medullary zone. Histologic signs associated with persistent diabetes mellitus are a general microangiopathy, typical annular nuclei of hepatocytes, island hyalinoses, island amyloidoses, and island fibroses of the pancreas. Histochemical tests can prove reduced zinc contents accompanied by a fibrosis of the exocrine pancreas. B-cell reduction of the Langerhans-islets is a specific indicator of the existence of juvenile diabetes Type I, associated with nodular glomerulosclerosis (Kimmelstiel-Wilson).

3.4.2 Biochemical findings

As a supplement to histomorphological findings it is necessary to conduct biochemical examinations when a diabetic coma or a fatal hypoglycaemia is suspected. Biochemical analysis can provide the best clues, including the determination of insulin or measuring C-peptide. Postmortal biochemical analyses require body fluids to be taken such as cerebrospinal fluid, vitreous humour, blood, and urine. The following parameters must be determined: glucose, lactate, HbA_{1c} , ketone bodies, insulin and C-peptide. The inversely exponential glucose decomposition of cerebrospinal fluid is about 10 to 15 mg/dl per hour which means that it takes normally 10 to 12 hours until no glucose is remaining. If the existence of glucose can be proved after this time period, the existence of premortal hyperglycemia must be assumed. However, the evaluation of liquor glucose figures ranging normally between 50 and 90 mg/dl requires extraordinary care, because increases of the normal liquor glucose percentages can also be caused by other mechanisms such as CO-intoxication, trauma of the CNS, protracted agony, and others. Lactate concentration in cerebrospinal fluid is normally about 9 mg/dl; however, due to glycolysis in the post mortal phase there is an increase of about 10 to 15 mg/dl per hour until the tenth hour post mortem. Particular caution is required also for the interpretation of the lactate figures. We apply a combined method according to Traub and sum up lactate and glucose. Our calculation is based on the principle that one mole glucose produces 2 moles of lactate. The straight addition of the measured values can be performed when they are taken in the unit “mg/dl”. We consider 362 mg/dl to be the upper limit of the normal additional value in the cerebrospinal fluid. Any figures exceeding this value disclose metabolic imbalance, but they must be evaluated very critically. The same method using the total of glucose and lactate is also applied to vitreous humour.

Determination of glucose and lactate in blood did not prove to be useful, if blood of the right ventricle is used. The figures might be increased due to the hepatic glycogenolysis. Normally, however, postmortal glycolysis reduces within six to eight hours glucose in the blood to 0 mg/dl. Postmortal diffusion of serum and substrate from the tissues into the blood are so unpredictable that the application of the empirical formula according to Traub is not possible.

Another important parameter is the determination of hemoglobin A_{IC} (Hb A_{IC}). In this case a molecule of glucose is non-enzymatically added to the Hb-molecule (glycolized hemoglobin). As for the diagnosis of comatous condition , increased totals according to Traub, urinary glucose and Hb A_{IC} are applicable. Since Hb A_{IC} is relatively resistant to autolysis, its postmortal existence continues to be provable in frozen condition or when stored at +4°C temperature, for a considerable time period. Hb A_{IC} figures exceeding 12% are considered to be an indicator.

Moreover, we refer to the determination of ketone bodies such as acetone, acetoacetate and ß-hydroxybutyrate whose concentrations are high in the presence of extraordinary ketotic metabolic disorder. As a rule, tracing of free acetone is performed by gas chromatography procedures together with blood alcohol determination; when acetone values exceed 5 mg/dl, the existence of diabetes must be considered.

As for the unrine anaylsis, glucose concentrations exceeding 25mg/dl are an indicator for diabetes, however the possibility must be considered that the glucose increase mght have been conditioned by other circumstances such as cerebral trauma. Considering the ketone bodies, an increase of free acetone superior to 0.5 mg/dl is an indicator of the existence of a ketotic metabolic disorder. Diagnosis of hypoglycaemias is a considerable problem. They are divided into exogenous and endogenous hypoglycaemia. Exogenous hypoglycaemia is triggered by erroneous or intentional administration of insulin or sulfonylurea. Endogenous hypoglycaemias are observed, among others, in the presence of diseases such as insulinoma or when a person abstains from food after excessive alcohol consumption.

According to Traub, low totals detected in liquour (inferior to 50 mg/dl and in the vitreous humour inferior to 100 mg/dl) with simultaneous high insulin concentrations indicate the existence of hypoglycaemia. We would like to draw your attention to the fact that the intake of sulfonylurea will trigger an increase of insulin and C-peptide.

3.5 Particularities as to the microsopic examinations of the heart

Considering the eminent importance of the question if cardiac failure – e.g. of inflammatory origin - could have caused the accident, the hearts of crew members have been examined by special methods for many years. If for the assessment of the cardiac condition only a few sections are performed at the left and at the right-hand side of the heart, this assessment applies just to the area which was examined. Since inflammatory processes can occur at any point at different cardiac regions - we have decided a couple of years ago to take samples from 19 places of the heart and to provide complete section and evaluation of the coronaries in each and every aircraft crash victim. The places for sampling are chosen in accordance with DOERR's examinations regarding the distribution pattern of infiltrates which occur during myocarditis of different causes. So, we have gained experience with more than 100 cases in the course of the passed eight years.

I would like to show you three cases:

When approaching his main operating base, an antiarmor helicopter suddenly took to a steep descent and crashed into a meadow. Technical investigation found out that this attitude could only have been caused by sudden lowering of the so-called collective pitch lever. When the autopsy was performed, macroscopically no essential pathological findings were achieved regarding the organs. In order to rule out a sudden conductive disturbance, the whole ventricular septum was investigated in about 2000 step sections which exceeded the normal scheme of sampling. The septum disclosed several small lymphocytic infiltrations outside of the pathways without any secure signs of muscle cell necroses which could be followed for about half a millimeter. According to the DALLAS criteria this finding corresponds to an idiopathic borderline myocarditis. Additionally, lymphocytes and plasma cells proved to be accumulated on various places in the lymphatics; the former can be interpreted as drainage of various foci of inflammation which could be proved to exist. In the evaluation however, we considered it rather improbable that the airworthiness should be hampered by such findings, since the distance of the infiltrations was too far from the pathways and also taking slightly distinct clinical cardiovascular features into account.

The second case is as follows: A Tornado fighter jet pilot performed 15 attacks to a ground target with low acceleration forces. In the approaches 16 and 17, acceleration forces increased to 6 G which means that the gravitational acceleration was sixfold. In his 17th approach the pilot initiated the inception turn too late and crashed against a bunker building.

Macroscopical examinations of the organs did not yield any essential pathological findings. Histological examination revealed multiple netlike fibroses of the myocardium and medial and intimal hypertrophy of the arterioles. In some sections, the Luxol-Fast-Blue staining showed the characteristics of diffuse myofibrillar degeneration. Several areas were found, where cardiac muscle fibers in wavy course bordered on distinctly fragmented myocyte bundles. Of late, this change is interpreted to be an indication of a beginning myocardial damage.

Attending to the clinically recorded distinctive features - particularly in the exercise electrocardiogram and from the aeromedical point of view - an acute functional impairment of the myocardium under the sudden excessive G-loads cannot be ruled out to have been the cause of the aircraft crash.

The third case: This case is supposed to demonstrate that extensive cardiac investigation is also rewarding in other circumstances.

Under the microscope, the myocardium of a patient who had suffered from tuberculosis showed several tubercles which were located at the right posterior auricle and at the left posterior ventricular wall close to the base; such tubercles explained sudden death although pulmonary findings had improved. Molecular genetic investigation proved bacterial genome to exist in those areas and thus a rare case of tuberculous myocarditis could be verified according to the pertinent literature.

Since pathological changes of the myocardium can occur at diverse places and since foci of inflammatory alterations close to the conduction pathways - in particular - can trigger disturbances of spread of stimulus, the interpretation of just a few histological sections performed at only one place of the right and the left ventricular wall do not prove very much. Therefore, extraordinary expenses and efforts are required and a large number particularly of critical regions of the myocardium need to be investigated.

4 FINAL REMARKS

Apart from the problem areas which were mentioned regarding the toxicological and pathological examinations, diverse other fields would have to be discussed critically, such as interpretation of vital reactions, appreciation of the time, when injuries were inflicted, ability to act after having suffered different types of trauma, and the evaluation of toxicological tests which were performed with hairs, or the differentiation between real drug consumption and having eaten a piece of poppy seed cake, for example.

Only if all aircraft accidents and incidents are continuously examined subtly and in every detail, attending to a very high investigation standard, a high degree of flight safety can be achieved. This means that the examinations which must necessarily be performed for securing the evidence and clarification, if the accident could have been avoided, exceed by far the extent of the investigation which would be required for criminal appraisal only.

Human Tolerance and Crash Survivability

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ABSTRACT

Aircraft and motor vehicle crashes will continue to occur in spite of all human efforts to prevent them. However, serious injury and death are not inevitable consequences of these crashes. It has been estimated that approximately 85 percent of all aircraft crashes are potentially survivable without serious injury for the occupants of these aircraft. Nevertheless, many deaths and serious injuries occur in crashes that are classified as "survivable". This is because the protective systems within the aircraft such as seats, restraint systems, and cabin strength were inadequate to protect the occupants in a crash that would have otherwise been non-injurious. In order to maximize survivability in a crash, one must have an understanding of the tolerance of humans to abrupt acceleration and then design an aircraft that is capable of maintaining its cabin/cockpit integrity up to the limits of human tolerance. This should be combined with judicious use of energy absorbing technologies that reduce accelerations experienced by the occupants and by restraint systems that provide appropriate support and prevent injurious contacts. This paper discusses basic principles of human tolerance to abrupt acceleration as well as basic concepts of crashworthiness design. Although these concepts are discussed in the context of helicopter crashes, the same principles apply to other vehicles.

INTRODUCTION

Aircraft and motor vehicle crashes will continue to occur in spite of all human efforts to prevent them. However, serious injury and death are not inevitable consequences of these crashes. It has been estimated that approximately 85 percent of all aircraft crashes are potentially survivable without serious injury for the occupants of these aircraft (1,2,3). This estimate is based upon the determination that 85 percent of all crashes met two basic criteria. First, the forces involved in the crash were within the limits of human tolerance without serious injury to abrupt acceleration (1). Second, the structure within the occupant's immediate environment remained substantially intact, providing a livable volume throughout the crash sequence (1). In other words, contrary to popular belief, most aircraft crashes are not "smoking holes".

Nevertheless, many deaths and serious injuries occur in crashes that were classified as "survivable" by crash investigators. This is because the protective systems within the aircraft such as cabin strength, seats, and restraint systems were inadequate to protect the occupants in a crash that would have otherwise been non-injurious. This is why the definition of survivability of a crash is based solely on aircraft and impact related factors and not upon the outcome for the occupants of the crashed aircraft. A mismatch between the survivability of the crash and the outcome for the occupants suggests an inadequacy of protective systems design or utilization.

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It should also be recognized that transmission of forces to the occupants as well as the degree a vehicle maintains its structural integrity during a crash, the two components of survivability, are determined, in large part, by the design of the vehicle. The process of establishing the degree to which any particular vehicle will protect occupants in a crash, or its crashworthiness, involves a series of trade-off decisions during its design and manufacture. One of the adages of aircraft design, "it is possible to build a brick outhouse, but you can't make it fly", applies to this situation. Increased crashworthiness and advanced crash protection systems increase both the cost and the weight of the final design and, therefore, potentially decrease profit margins as well as aircraft performance. The "trade-off" is to provide the right degree of protection for the projected crash environment without sacrificing too much in terms of cost or performance. Obviously, the bases for determining the "right" trade-off are frequently the source of considerable debate both during the design phase and over the lifetime of any vehicle. One recurring error in these trade-off decisions is a lack of understanding of human tolerance and protection concepts by the decision makers as well as a failure to adequately determine or estimate the crash environment.

The other factor entering into this process is government design requirements. These requirements are also the result of considerable compromise made more for political and economic reasons than for their technical merit. Suffice it to say that Federal design standards should be considered minimal requirements and not representative of the current state-of-the-art in occupant protection.

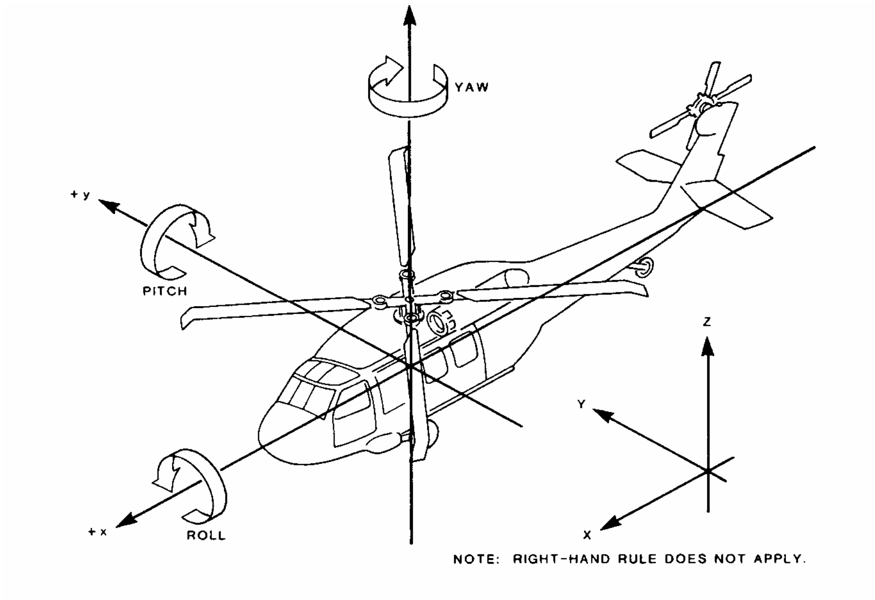
To fully understand these issues requires a clear comprehension of the crash environment to which any particular vehicle is exposed as well as an understanding of human tolerance to acceleration and the basic principles of occupant crash protection. The purpose of this paper is to introduce the reader to some of the more basic concepts relating to personal survival in aircraft and other vehicular crashes.

COORDINATE SYSTEMS

1. Injury in a crash is the result of human response to force application to the body. Force and acceleration are vector quantities comprising both magnitude and direction.
2. For purposes of description, both the aircraft and the seated human are arbitrarily assigned coordinate axes which are related as follows (Figures 1 and 2):

Aircraft	Human
Roll	X
Pitch	Y
Yaw	Z

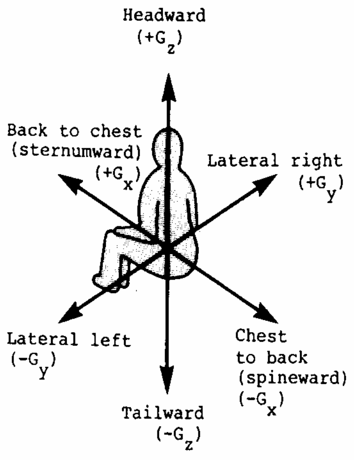
3. Any applied force or acceleration may be described according to its components directed along each of the orthogonal axes.
4. Figure 1 is a representation of the aircraft coordinate system commonly used in military and other government publications and standards. It represents a "left-hand rule" coordinate system (1). It should be noted that there are other coordinate systems in use, and it is important for the reader to establish which system is in use for any particular publication or standard.



NOTE: RIGHT-HAND RULE DOES NOT APPLY.

Figure 1. Aircraft coordinates

5. Figure 2 depicts a commonly used coordinate system applied to the seated human. The reference to movement of the eyeballs describes the body's inertial reaction to the applied acceleration, which is opposite and equal to the applied acceleration (1). It is the body's inertial response to an acceleration that results in injury.



Direction of accelerative force

Vertical

Headward - Eyeballs-down
Tailward - Eyeballs-up

Transverse

Lateral right - Eyeballs-left
Lateral left - Eyeballs-right
Back to chest - Eyeballs-in
Chest to back - Eyeballs-out

Note:

The accelerative force on the body acts in the same direction as the arrows.

Figure 2. Human coordinate system

ACCELERATION

1. Acceleration is defined as the rate of change in velocity of a mass and is frequently stated in units of feet per second per second or feet/second^2 (meters/second^2. It is related to force by the familiar equation, $F = ma$, where F = force, m = mass, and a = acceleration.
2. Acceleration may be described in units of G which is the ratio of a particular acceleration (a) to the acceleration of gravity at sea level ($g = 32.2$ ft/sec^2 or 9.8 m/sec^2) or $G = a/g$. As a result, crash forces can be thought of in terms of multiples of the weight of the objects being accelerated.
3. Acceleration values given in various reports generally refer to the acceleration of the vehicle near its center of mass, unless otherwise specified.
4. Note that a deceleration is simply a negative acceleration.
5. An impact or crash is frequently described in terms of a crash pulse (Figure 3). A crash pulse is a description of the accelerations occurring in the crash over time, or the acceleration-time history of the crash. Although the shape of a crash pulse can be highly complex and variable from crash to crash, for practical purposes, most aircraft and automobile crash pulses may be considered to be generally triangular in shape. This assumption vastly simplifies calculations related to the crash and provides reasonable estimates of acceleration exposure for field investigators. Note that in a triangular pulse, the average acceleration of a pulse is one-half of the peak acceleration.

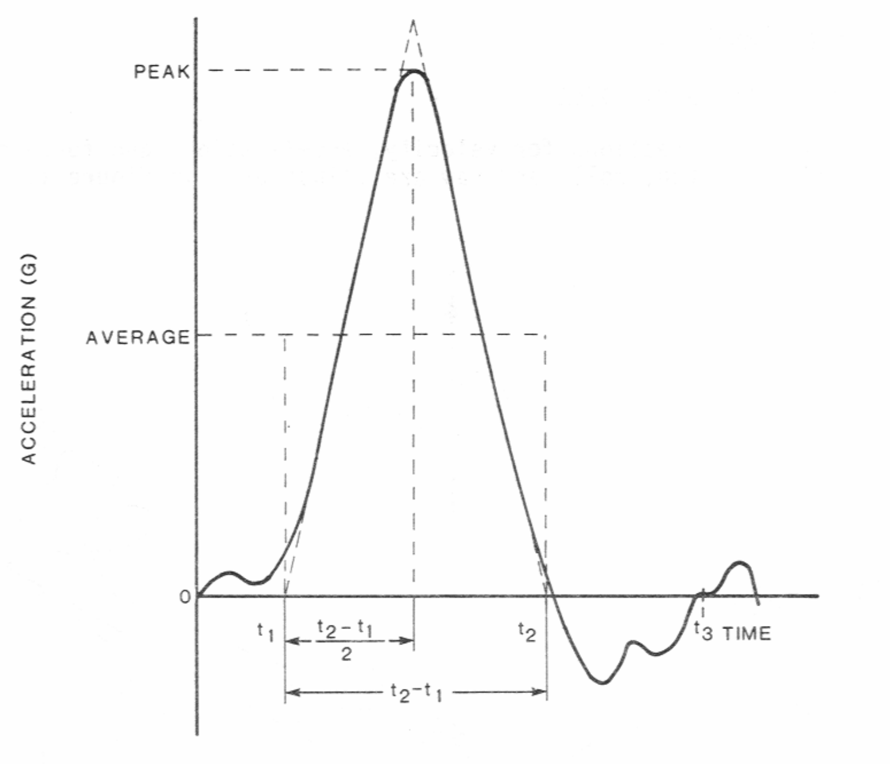


Figure 3. Triangular Crash Pulse

6. If the velocity of the vehicle at the time of the crash can be estimated and the stopping distance (vehicle crush plus soil deformation) measured then the acceleration of the vehicle during the crash can be estimated through a simple formula, assuming a triangular pulse:

a. Peak G = $$\frac{v^2}{(g) \times s}$$

where v = velocity change of the impact,
s = stopping distance and,
g = acceleration of gravity at sea level = 32.2 ft/s^2 or 9.8 m/s^2

b. Average G is equal to one half of the peak G.

TOLERANCE TO ABRUPT ACCELERATION

1. An understanding of human tolerance to abrupt acceleration is essential to developing appropriate crashworthiness or protective system design standards for any vehicle. If one knows the crash environment to which a vehicle will be exposed and the limits of human tolerance to acceleration, then one can rationally develop crashworthiness design requirements to protect occupants in foreseeable crashes of that vehicle.
2. In general, human tolerance to acceleration is a function of five extrinsic factors (5). These factors are related to characteristics of the crash pulse and to the design of the seating and restraint systems:
   a. **Magnitude** of the acceleration

      Clearly, the higher the acceleration, the more likely it is to cause injury.

   b. **Direction** of the acceleration

      The human is better able to withstand accelerations applied along certain axes of the body (Figures 4 and 6). The direction that is most tolerable is the $+G_x$ or acceleration in the forward direction (eyeballs in). The least tolerable direction is apparently the G_z or vertical axis (eyeballs up or down). The lateral axis (G_y) used to be considered the least tolerable, but recent data derived from crashes of Indianapolis Race Cars indicates that this is probably not the case.

   c. **Duration** of the acceleration

      How long one is subjected to an acceleration is one of the determinants of human tolerance. In general, the shorter the pulse for the same magnitude of acceleration, the more tolerable (Figures 4 and 6). Acceleration tolerance is usually considered to comprise two distinct realms—abrupt acceleration and sustained acceleration—because of distinctly different human response patterns to abrupt and sustained accelerations. Most crash impacts have a duration of less than 250 milliseconds or one-quarter of a second, which is considered to be in the realm of abrupt acceleration. Human tissues and the vascular system respond considerably differently to these very short duration pulses than they do the more sustained pulses experienced by fighter pilots and astronauts. Consequently, a 10 G turn or “pull-up” may cause unconsciousness in a pilot and result in a crash, but a 10 G crash impact may have little effect on the occupant of an automobile or aircraft.

   d. **Rate** of onset

      Rate of onset of acceleration refers to how rapidly the acceleration is applied. It is reflected in the slope of the curve depicted in figure 3. For a given magnitude and duration of acceleration, the greater the rate of onset, the less tolerable the acceleration (Figure 5).

   e. **Position/Restraint/Support**

      This is one of the most critical factors determining human tolerance to a crash pulse. It refers to how well the occupant is restrained and supported by his seat and restraint system and the degree to which the loads experienced in the crash are distributed over his body surface. It is this factor that is the primary determinant of lack of survival in a survivable crash, if post-crash fire is excluded.

3. Also of importance in considering human tolerance to abrupt acceleration are various intrinsic factors, or factors that are directly related to the individual subjected to the impact. These factors are independent of the extrinsic factors discussed above. They, in large part, explain the observed biological variability of humans subjected to identical impacts:
    a. **Age** of the subject

       Young, healthy adults are best able to withstand impact accelerations. Consequently, a vehicle designed for military applications may allow more severe accelerations to be experienced by occupants than a vehicle intended for the general population.
    b. **Health** of subject

       Chronic medical conditions such as heart disease and osteoporosis, clearly degrade one's ability to withstand impact accelerations. History of previous injuries may also adversely affect one's tolerance.
    c. **Sex** of subject

       There are clearly sex differences in tolerance to acceleration. Women have a different mass distribution than men as well as differences in muscle mass. This has been of particular concern for the neck where women have approximately one third less muscle mass than men of comparable stature.
    d. **Physical conditioning**

       Physical conditioning appears to increase ones tolerance both to abrupt and sustained acceleration, probably due to increases in muscle mass and strength. Physical conditioning is also considered to be a factor in recovery from injuries.
    e. **Other** factors

       Certainly, there are other intrinsic factors that affect one's ability to withstand acceleration. Unfortunately, these various factors will probably remain somewhat nebulous due to the obvious limitations on performing research in this area.

HUMAN TOLERANCE CURVES (EIBAND CURVES)

1. In 1959, Eiband compiled what was then known about the tolerance of a restrained individual to abrupt accelerations (1). These data were compiled primarily from the pioneering work of Colonel John Stapp who performed human tolerance experiments on live volunteers, himself and coworkers, using acceleration sleds and other acceleration devices. Eiband also included in his summary, human surrogate experiments that had also been performed. The tolerance curves that Eiband constructed are illustrated below in Figures 4 and 6.
2. Figure 4 is the Eiband Curve for accelerations in the $+G_z$ axis, analogous to the direction of forces experienced in an ejection seat or a vertical crash of a helicopter. It is a plot of uniform acceleration of the vehicle as demonstrated in the lower right-hand corner, versus the duration of the acceleration for pulses up to approximately 150 milliseconds. As the legend on the graphs notes, these exposures were all survivable with essentially idealized seat and restraint systems. The graph illustrates that individuals voluntarily tolerate accelerations up to approximately 18 G without injury, and spinal injury does not occur below accelerations of approximately 20-25 G.
3. Figure 6 depicts the analogous curve for the $-G_x$ direction, such as would be experienced in a head-on collision. Note that the tolerance in this axis is over 40 G.
4. Similar curves are available for the other axes. A summary of estimates of human tolerance in all axes is shown below:

Human Tolerance Limits

Direction of Accelerative Force	Occupant's Inertial Response	Tolerance Level
Headward (+ Gz)	Eyeballs Down	20-25 G
Tailward (- Gz)	Eyeballs Up	15 G
Lateral Right (+ Gy)	Eyeballs Left	20 G
Lateral Left (- Gy)	Eyeballs Right	20 G
Back to Chest (+Gx)	Eyeballs Out	45 G
Chest to Back (- Gx)	Eyeballs In	45 G

Note: Reference: Crash Survival Design Guide, TR 79-22.
(0.10 Second time duration of crash pulse; full restraint)

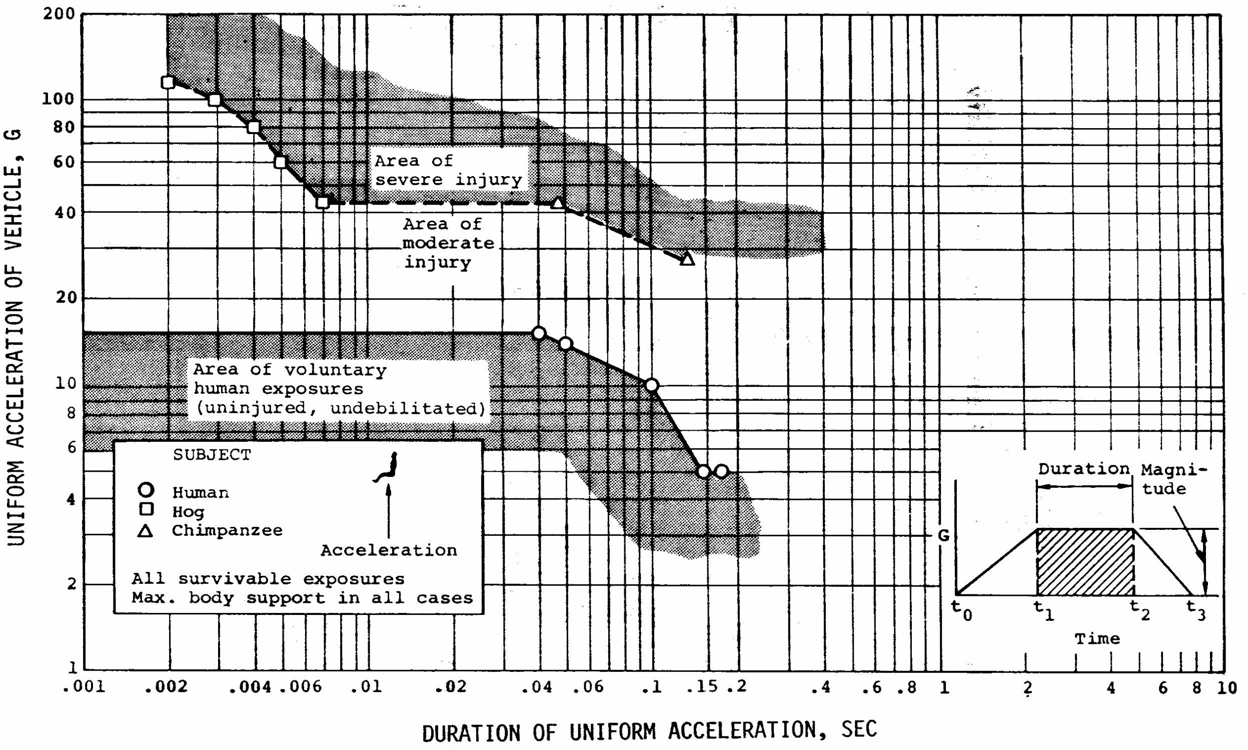


Figure 4. Eiband Curve for $+G_z$

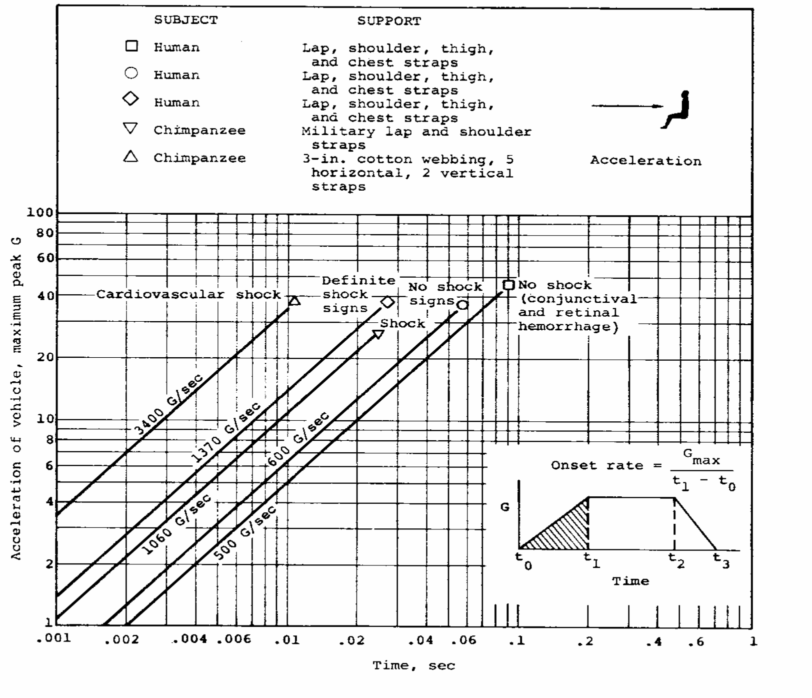


Figure 5. Effect of Rate of Onset

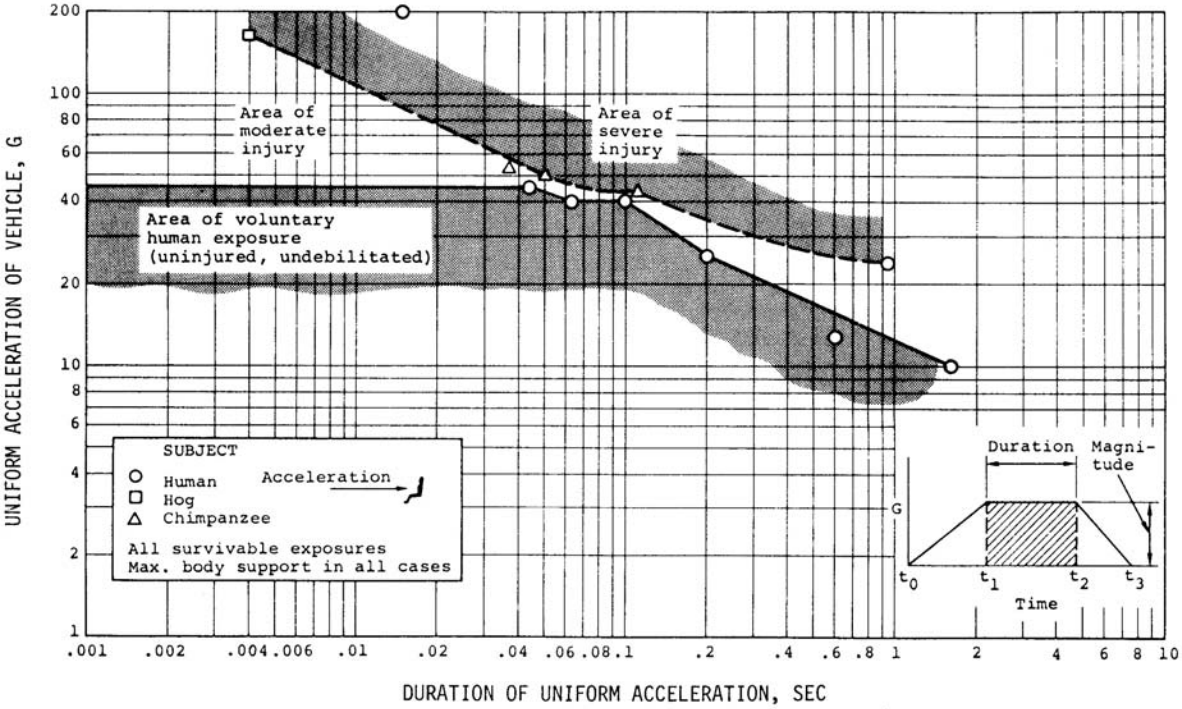


Figure 6. Eiband Curve for $-G_x$

CLASSIFICATION OF TRAUMATIC INJURY

1. At the risk of oversimplifying the issue, it is useful from a designer's or investigator's standpoint to divide injury suffered in vehicular crashes into **mechanical injury** and **environmental injury**. Mechanical injury is further subdivided into **contact injury** and **acceleration injury** (4). Environmental injury refers to burns, both chemical and thermal, and events such as drowning.
2. In a strict sense both acceleration and contact injuries arise from application of force to the body through an area of contact with an accelerating surface. In the case of acceleration injury, the application is more distributed so that the site of force application usually does not receive a significant injury. The site of injury is distant from the area of application and is due to the body's inertial response to the acceleration. An example of acceleration injury is rupture of the aorta in a high sink rate crash. Here the application of force occurs through the individual's thighs, buttocks, and back where he is in contact with the seat. The injury itself is due to shearing forces at the aorta generated from the inertial response of the heart and aorta to the upward acceleration of the body.
3. A contact injury occurs when a localized portion of the body comes into contact with a surface in such a manner that injury occurs at the site of the contact ("the secondary collision"). Relative motion between the body part and the contacting surface is required. An example of this type of injury is a depressed skull fracture resulting from the head striking a bulkhead.
4. A mixed form of injury may also occur when acceleration generated by a localized contact produces injury at a site distant from the point of contact as well as at the point of contact. An example of this type of injury is a contracoup brain injury.
5. Distinction is made between these two basic forms of injury since prevention involves different strategies. Providing means of absorbing the energy of a crash before it can be transmitted to an occupant prevents acceleration injury. Structural crush zones, energy absorbing seats, and energy absorbing landing gear all provide this function.
6. The primary strategy employed to prevent contact injury, on the other hand, is to prevent the contact between the occupant and a potentially injurious object. This can be accomplished through a variety of methods including improved occupant restraint or relocation of the potentially injurious object. If contact cannot be prevented, injury can be mitigated by reducing the consequences of body contact through such strategies as padding of the object, or making the object frangible so that contact causes the object to yield before injury occurs.

RESTRAINT ISSUES

1. As discussed above, good restraint is critical to survival in all but the most minor impacts. Restraint systems serve many important functions including:
   a. Preventing ejection of occupants from their seats or the vehicle
   b. Preventing the "secondary collision" which refers to body impact with interior structures in the vehicle such as windshields, controls, and instrument panels due to flailing of the body in response to accelerations caused by the vehicle collision.
   c. Distributing crash loads over a wide portion of the body. This is essential in frontal impacts for forward facing occupants. Properly designed restraints also ensure these loads are borne by the portions of the body most able to withstand dynamic forces namely the pelvis, chest, and shoulder girdle. Restraints that contact the neck or ride up into the abdomen can result in dire consequences for the occupant in relatively minor impacts.
   d. Tightly coupling the body to the vehicle, thus preventing magnification of forces due the development of relative velocities between the decelerating vehicle and its occupants (dynamic overshoot).
   e. Providing for "ride down" of the crash forces.

2. Prevention of the secondary collision is essential to crash survival since relatively minor crashes can result in fatal impacts with interior vehicle structures. There are many different types of belt restraint systems available today, but they mainly involve either pelvic restraint (lap belt) or upper torso restraint (shoulder belt) or a combination of both (3-point, 4-point, and 5-point systems).
3. Lap belt only configurations (2-point restraints) permit tremendous flail of the upper torso in crashes as shown in Figure 6. The upper torso flail illustrated in this figure is for a 95th percentile male Army aviator subjected to a 30 G forward and 30 G lateral impact on an acceleration sled (1). The amount of excursion depicted is the average of a number of tests. With a head excursion of approximately 40 inches (102 cm.) in the forward direction, it can be seen why lap belt only restraint will not protect a driver of a car or pilot of an aircraft from impact with control surfaces or the instrument panel.
4. Figure 7 illustrates how these strike envelopes are significantly reduced for the same impact conditions when dual harness upper torso restraint and tie-down strap is added to the system (5-point restraint).
5. An Additional advantage offered by upper torso restraint in combination with pelvic restraint is that multi-belt restraints provide additional distribution of impact loads across the upper torso instead of focusing the entire load across a 2 to 3 inch strip across the pelvis.
6. Upper torso restraint and tie-down straps also help prevent a situation known as “submarining” from occurring (Figure 7). This is where the lap belt rides over the pelvic brim and compresses the soft tissues of the abdomen resulting in serious abdominal and spinal injuries. Submarining occurs due to the pelvis rotating under the lap belt, usually due to inappropriate location of the lap belt anchors or due to poor design of the seat bottom or a combination of both. Lap belt only restraints so commonly inflicted serious injuries on users in automobile crashes that the medical community coined a new term, “the seat belt syndrome”, to describe the constellation of injuries caused by submarining under the lap belt (6, 9, 10).
7. An exciting new development in helicopter restraint systems is the planned implementation of inflatable restraint systems in Army helicopters. These systems include air bag systems similar to those used in automobiles as well as inflatable bags contained in belt restraint systems intended to provide pretensioning and body support. Such systems are projected to reduce injury in crashes of some helicopters by as much as 30 percent.

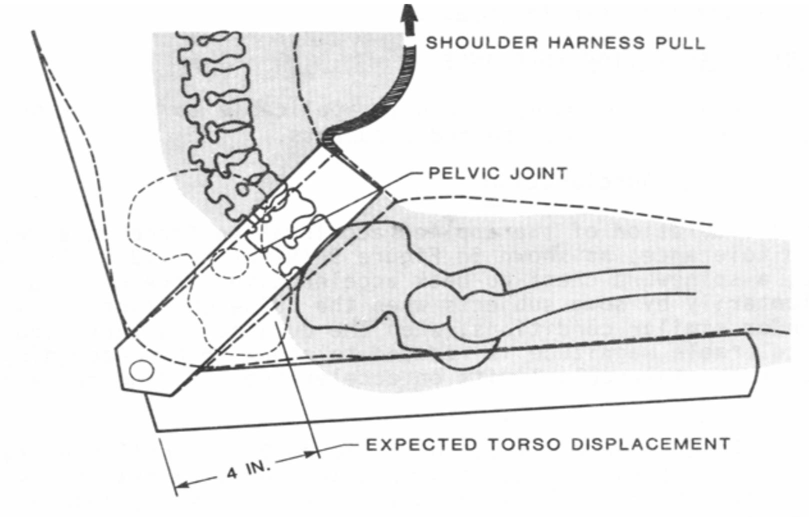


Figure 7. Submarining

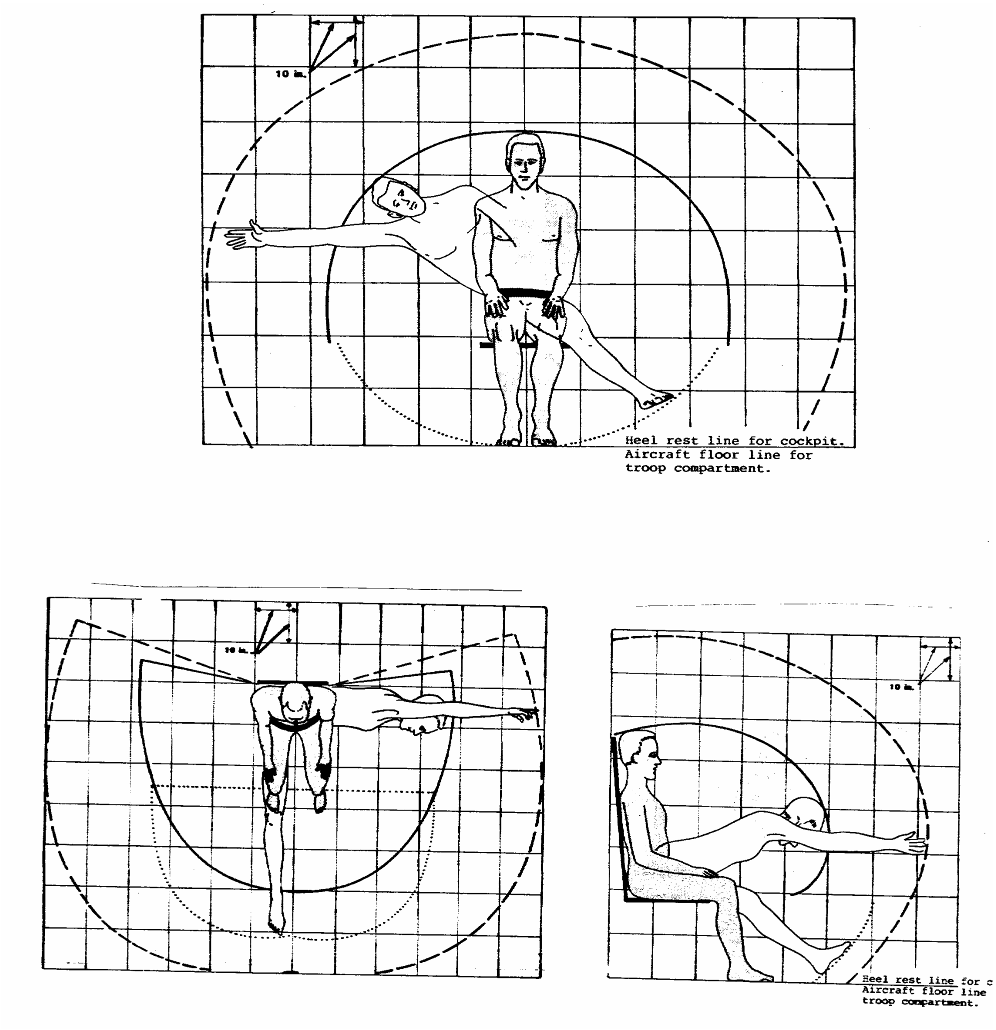


Figure 8. Strike Envelope for Lap Belt Restraint

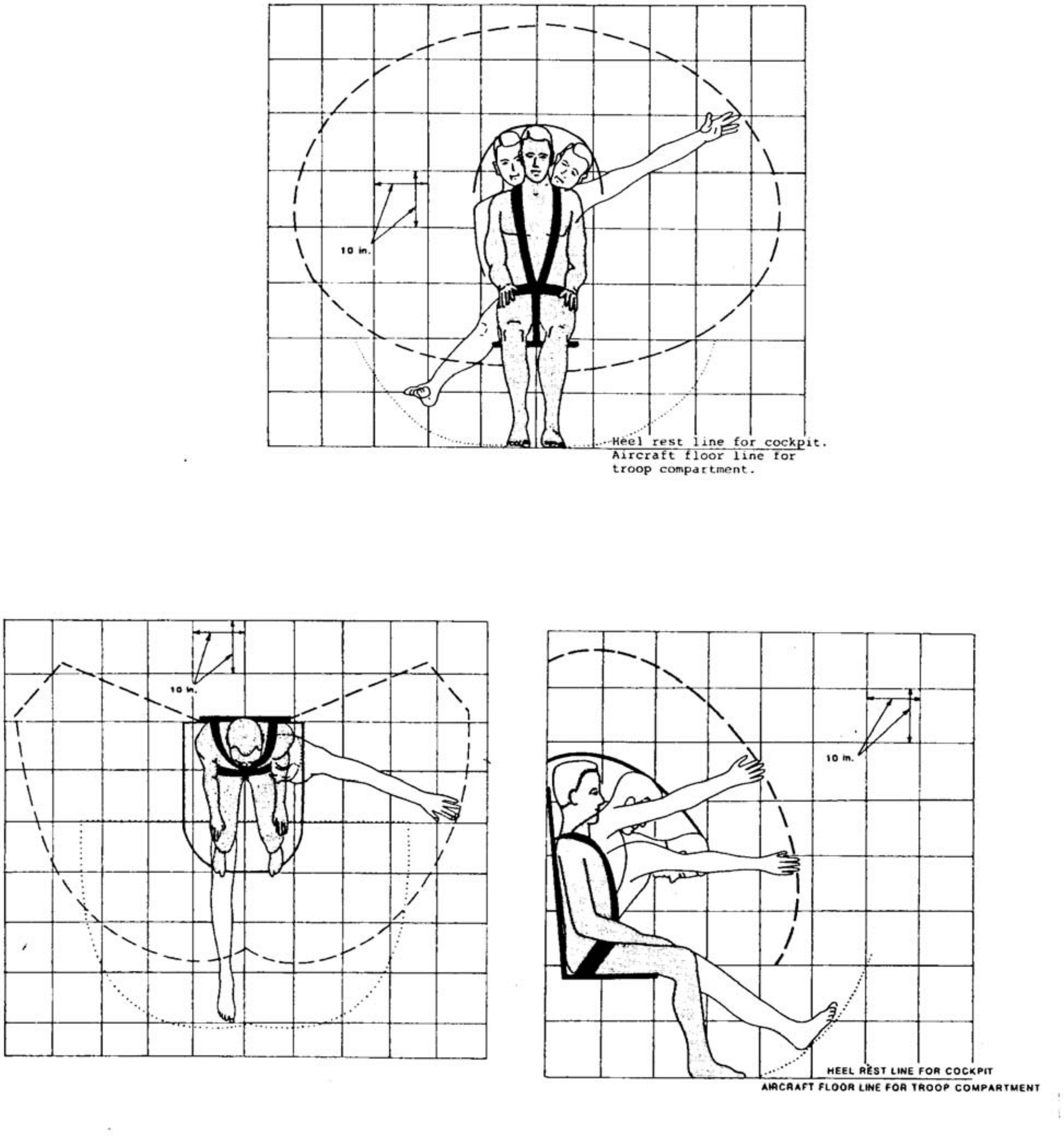


Figure 9. Strike Envelope for 5-Point Restraint.

PERSONAL SURVIVAL IN VEHICULAR CRASHES

1. The above discussion was directed toward human tolerance to impact for relatively ideally restrained occupants subjected to abrupt accelerations. In practice, occupants are rarely ideally restrained and there are many other factors beside restraint and acceleration involved in the crash, which determine whether a person is injured, or not.
2. In analyzing personal outcome for individuals involved in a particular crash, many investigators use what is known as the "CREEP Principle". CREEP is merely an acronym for the five factors considered to influence personal survival in a crash. Although these factors may not encompass the entire complex set of factors involved in surviving a crash, they provide an extremely useful framework for conducting a systematic analysis (5) of personal survival. The five factors are:
    a. **C**ontainer

        The potential for survival during a crash is severely compromised if the occupied spaces collapse or are penetrated by external objects.

    b. **R**estraint

        Effective personal restraint is essential for injury prevention in all but the most minor crashes. Of almost equal importance is restraint of potentially injurious objects within the cabin space such as cargo and luggage.

    c. **E**nvironment

        This refers to potentially injurious objects located within the strike zone of each occupant. Ideally restraints systems should prevent occupant contact with internal structures. If the strike cannot be prevented in foreseeable crashes, then the object should be relocated, or if this is not feasible, it should be rendered non-injurious by padding or frangibility.

    d. **E**nergy Absorption

        In severe crashes, accelerations may exceed human tolerance limits in spite of excellent restraint and seat systems. Under these circumstances, providing means of managing the energy of the crash in a controlled manner can greatly increase the survivability envelope. Automobile designers accomplish this by providing "crush zones" in the front and rear of automobiles wherein crushing of the vehicle structure absorbs a portion of the energy of the crash, thus reducing the forces experienced by the occupants. Helicopters tend to crash mainly in a vertical direction creating very high accelerations in the vertical axis. Rather than increasing structure in the bottom of helicopters to help absorb energy in these crashes, many military helicopters are provided with energy absorbing seats. These seats stroke vertically in a crash, thus absorbing energy and reducing accelerationss experienced by the occupants. Fixed landing gear can also be designed to absorb a considerable portion of the energy in vertical impacts.

    e. **P**ost-Crash Factors

        In many crashes, the occupants survive the crash only to succumb to post-crash hazards such as fire, drowning or natural environmental elements such as heat and cold. These conditions are frequently aggravated by an inability to egress the crashed aircraft, due to obstructions within the aircraft, blockage or malfunctioning of emergency exits, or an insufficient number or size of exits.
3. All of the factors listed above should be considered in the analysis of any vehicular crash. Collectively, knowledge gained from individual crashes can be used to detect trends and provide information that can help manufacturers and regulators develop improved means of protecting occupants in a crash. Unfortunately, such data also documents needless injuries and deaths, which subsequently provide the "blood priorities" often-required before necessary improvements in regulations or design are effected.

4. An excellent example of effective technology for preventing injury in crashes, which has been extremely slowly adopted, is the use of crashworthy or crash resistant fuel systems (CWFS/CRFS) in helicopters. These are fuel systems that are designed to completely contain fuel in potentially survivable crashes and, thus, prevent fuel fed post-crash fires. The U.S. Army experience revealed that in Viet Nam era helicopters approximately 40 percent of fatal injuries in survivable crashes were due to post-crash fires. This led the Army to develop and install CWFS on most of its helicopters. Since the introduction of CWFS into Army helicopters, there have only been one or two documented deaths due to thermal injury in survivable crashes of CWFS equipped helicopters. This was a remarkable achievement; particularly considering the cost of retrofitting these systems to Army helicopters was relatively low. For example, the cost of modifying a UH1-H in the mid-1970's was $7,517 with a weight penalty of 160 pounds and a reduction in fuel capacity of only 11 gallons (7). As effective as these systems are, they have only been slowly adopted by other military services, and they are rarely installed in civilian helicopters.
5. Other injury prevention technologies developed by the military such as energy absorbing seats and 5-point restraint systems, though perhaps less effective than CWFS, have also been slow to find their way into civilian applications. This is due to the reluctance of regulators to mandate their use, the reluctance of manufacturers to provide them as standard equipment or as an option, and reluctance of consumers to purchase them when offered as an option.

CONCLUSIONS

The human body is able to withstand remarkable crash forces if provided with appropriate restraint and if protected from collapsing structure and injurious interior objects. Vehicle designers can extend the envelope of survivability through intelligent crashworthiness designs that incorporate means of managing the energy of the crash as well as strengthening the space immediately surrounding occupants. The U.S. Army has proven that these protective technologies can be economically incorporated into helicopters such as the UH-60 Black Hawk, and the crash experience of this helicopter and others, have proven the efficacy of these crashworthiness concepts. The same concepts have been very effectively integrated into Indianapolis and NASCAR racecars with remarkable results. In fact, crash recorders installed in "Indy Cars" indicate that a properly protected human may be able to withstand accelerations considerably in excess of the 40 G limit previously determined by Colonel John Stapp and others. Several Indy car drivers have withstood impacts in excess of 100 G without serious injuries (8).

Some of this technology has been applied to automotive designs and, to a lesser degree, to civilian aircraft. Nevertheless, vehicles could be made considerably safer and more crashworthy. Unfortunately, progress in this area will require heightened awareness of both the problems and the possibilities by the general public, regulators, and legislators. Manufacturers will not be willing to perform the research and development required to incorporate significantly improved crashworthiness into their vehicles unless consumers make safety a priority and reveal their willingness to pay for it. Likewise, legislators and regulators will not be inclined to require significant improvements in crashworthiness or increase research funding in this area unless the public demands it. The potential for improvements in automobile and aircraft crash safety is enormous. Hopefully, the impetus for change will occur through education and increased public awareness.

SELECTED REFERENCES

1. Desjardins, S. H., Laananen, D. H., Singley, G. T., III: Aircraft crash survival design guide. Ft. Eustis, VA, Applied Technology Laboratory, US Army Research and Technology Laboratories (AVRADCOM), 1979; USARTL-TR-79-22A.

2. Haley, J. L., Jr.: Analysis of US Army helicopter accidents to define impact injury problems. In Linear acceleration of the impact type. Neuilly-sur-Seine, France, AGARD Conference Proceedings No. 88-71, 1971, pp. 9-1 to 9-12.
3. Haley, J. L., Jr., Hicks, J. E.: Crashworthiness versus cost: A study of Army rotary wing aircraft accidents in period Jan 70 through Dec 71. In Saczalski, K., et al. (eds): Aircraft Crashworthiness. Charlottesville, University Press of Virginia, 1975.
4. Shanahan, D. F., Shanahan, M. 0.: Injury in U.S. Army helicopter crashes October 1979-September 1985. J Trauma, **29**: 415-23, 1989.
5. Shanahan, D. F. : Basic principles of helicopter crashworthiness. Ft. Rucker, AL, U.S. Army Aeromedical Research Laboratory, 1993; USAARL TR-93-15.
6. Sims, J. K., Ebisu, R. J., Wong, R. K. M., et al.: Automobile accident occupant injuries. J. Coll. Emerg. Phys., **5**: 796-808, 1976.
7. Singley, G. T., III: Army aircraft occupant crash-impact protection. Army R, D & A, **22**(4): 10-12, 1981.
8. Society of Automotive Engineers. Indy racecar crash analysis. Automotive Engineering International, June 1999, 87-90.
9. Traylor, F. A., Morgan, W. W., Jr, Lucero, J. I., et al.: Abdominal trauma from seat belts. Am. Surg. **35**: 313-316, 1969.
10. Williams, J. S., Kirkpatrick, J. R.: The nature of seat belt injuries. J. Trauma, **11**: 207-218,1971.

Basic Principles of Crashworthiness

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ABSTRACT

Crashworthiness can be defined as the ability of an aircraft and its internal systems to protect occupants from injury in the event of a crash. In general, injury in aircraft crashes can be considered to arise from three distinct sources: (1) excessive acceleration forces; (2) direct trauma from contact with injurious surfaces, and; (3) exposure to environmental factors such as fire, smoke, water, and chemicals resulting in bums, drowning or asphyxiation. Consequently, effective crashworthiness designs must consider all possible sources of injury and eliminate or mitigate as many as practical for a given design impact limit. This involves considerations of (1) strength of the container (cockpit and cabin), (2) adequacy of seats and restraint systems, (3) adequacy of energy attenuation systems, (4) injurious objects in the local environment of occupants, and (5) post-crash factors, principally fire prevention and adequacy of escape routes. The U.S. Army UH-60 Black Hawk and AH-64 Apache helicopters were the first helicopters built to modem crashworthiness specifications. This paper uses investigations of crashes of these helicopters to illustrate basic crashworthiness principles and to demonstrate their effectiveness when systematically incorporated into helicopter designs.

INTRODUCTION

The concept of providing occupant crash protection in aircraft is almost as old as powered flight itself. The first few crashes of powered aircraft suggested the need for helmets to provide head protection and leather jackets to prevent serious abrasions. Although seat belts were first developed to retain pilots during acrobatic flight, it did not take long for pilots and designers to recognize the value of occupant retention in a crash. Nevertheless, it was not until the 1940's that scientists and designers, notably Hugh DeHaven and his colleagues, began seriously to approach crash survivability from a total system concept (DeHaven, 1969).

Although most of the current concepts of crash survivability were established over 50 years ago, implementation of these concepts into operational aircraft has been remarkably slow. In fact, fully integrated crashworthy designs had been limited to a few agricultural aircraft until the U.S. Army committed itself to improving the crash survivability of its helicopters during the conflict in Southeast Asia. This work lead to the publication of the Aircraft Crash Survival Design Guide, which is a compendium of crashworthy design criteria for light fixed-wing and rotary-wing aircraft (Department of the Army, 1989). The guide, now in its fifth edition, has become the primary source of information for crashworthy design criteria for helicopters and light airplanes. Indeed, the criteria specified in the Design Guide were used to establish the design specifications for the Army's UH-60 Black Hawk and AH-64 Apache helicopters and form the basis of the Army's current general crashworthiness design standard (Carnell, 1978; Department of Defense, 1984). The effectiveness of the crashworthiness concepts incorporated into the UH-60 and AH-64 has been proven in

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numerous crashes of these helicopters (Shanahan, 1991; Shanahan and Shanahan, 1989a and 1989b). Surprisingly, operators of civil helicopters and government regulators have been reluctant to incorporate similar design features into the civil helicopter fleet.

CRASH INJURY

It is imperative to understand that injury and death are not inevitable consequences of an aircraft crash. In fact, most epidemiological studies of crashes have shown that up to 90 percent of crashes are potentially survivable for the occupants (Bezreh, 1963; Haley, 1971; Haley and Hicks, 1975; Hicks, Adams, and Shanahan, 1982; Mattox, 1968; Sand, 1978; Shanahan and Shanahan, 1989b). This assessment is based on the fact that the forces in most crashes are sufficiently low that use of currently available airframe and component technology could prevent occupant injury.

In order to prevent injury in crashes, it logically follows that one must understand how injuries occur. Injury in crashes may be classified as either traumatic or environmental (Table I). Traumatic injury is due to an adverse transfer of mechanical energy to an individual and is the most common form of injury seen in helicopter crashes. Environmental injury is injury caused by environmental factors such as water leading to drowning, heat leading to burns, or fumes leading to asphyxiation. Environmental injury is usually the predominant form of injury for crashes occurring in water or when a major post crash fire occurs.

Table I.
Classification of helicopter crash injury mechanisms

A. Traumatic injury
   1. Acceleration
   2. Contact
   3. Mixed
B. Environmental injury
   1. Fire
   2. Drowning
   3. Heat/dehydration
   4. Cold
   5. Chemical exposure (fuel)

Traumatic injury can be described further as contact injury or acceleration injury. In a strict sense, both forms of injury arise from application of force to the body through an area of contact with an accelerating surface. In the case of acceleration injury, force application is more distributed so that the site of force application usually does not receive a significant injury. The site of injury is distant from the area of application and is due to the body's inertial response to the acceleration. An example of acceleration injury is rupture of the aorta in a high sink rate crash. Here the application of force occurs through the individual's thighs, buttocks, and back where he is in contact with the seat. The injury itself is due to shearing forces generated from the aorta's and heart's inertial response to the resulting upward acceleration of the body.

A contact injury, on the other hand, occurs when a localized portion of the body comes into contact with a surface in such a manner that injury occurs at the site of contact ("the secondary collision"). Relative motion between the body part and the contacting surface is required. An example of this type of injury is a depressed skull fracture resulting from the head striking a bulkhead or other rigid object. A mixed form of injury also may occur when acceleration generated by a localized contact produces injury at a site distant from the point of contact as well as at the point of contact. A localized head injury with contracoup brain injury is the classic example of this mixed form of injury.

Distinction is made between these various mechanisms of injury since their prevention necessarily involves different strategies. The prevention of acceleration injury requires the attenuation of loads in a crash so that excessive loads are not transmitted to an occupant. Typically this is achieved through the use of energy absorbing landing gear, crushable under floor structure and energy absorbing seats. Prevention of contact injury requires the implementation of strategies that will prevent body contact with potentially injurious objects. This may be achieved through body restraint systems, “ruggedized” airframe designs to prevent intrusion of structure or high mass components into occupied areas, and removal of or delethalization of objects within the potential strike zone of occupants. Prevention of environmental injury involves a host of strategies tailored to the particular environmental hazard of interest. Certainly, in this category, the most significant hazard is post crash fire.

BASIC PRINCIPLES OF CRASHWORTHY DESIGN

Crashworthiness can be defined as the ability of an aircraft and its internal systems and components to protect occupants from injury in the event of a crash. The precise relationship between a particular helicopter design and crash injury is complex and engineering solutions may be quite intricate. However, the basic principles of crashworthiness design are quite straightforward, even intuitive. These principles may be summarized by the acronym “CREEP" as follows:

C - Container
R - Restraint
E - Energy absorption
E - Environment (local)
P - Postcrash factors

CONTAINER

The container is the occupiable portion of the helicopter--the cockpit and cabin. It should possess sufficient strength to prevent intrusion of structure into occupied spaces during a survivable crash, thus maintaining a protective shell around all occupants. Since structural collapse causing severe contact injury is one of the most frequent injury hazards encountered in helicopter crashes, this point cannot be overemphasized (Figure l).

Figure 1. A crash of a UH-60 where the roof completely collapsed, crushing the two rear occupants.

The container must also be designed to prevent penetration of external objects into occupied spaces. Another issue related to the container is high mass item retention. Transmissions, rotor systems, and engines should have sufficient tie-down strength to ensure that they do not break away and enter occupied spaces in survivable crashes. Finally, the belly and the nose of the helicopter should possess sufficient structural strength and be shaped so as to prevent plowing or scooping of earth during crashes with significant longitudinal velocity since plowing decreases stopping distances and results in-higher decelerative loads. In general, cockpit/cabin designs should allow for no more than 15 percent dynamic deformation when subjected to the design crash pulse.

RESTRAINT

A frequent occurrence in aircraft crashes is that either the seat tears from its attachments or the restraint system fails (Figures 2 and 3). This results in ejection of the occupant or it allows him/her to strike injurious objects. Regardless of the strength of the container, if the occupant is not appropriately restrained throughout the crash sequence, the chances of survival are severely reduced. Seats, restraint systems, and their attachments should have sufficient strength to retain all occupants for the maximum survivable crash pulse. In addition, seat attachments should be designed to accommodate significant degrees of floor warpage without failure. Since contact injury occurs at least five times more frequently than acceleration injury, careful consideration should be given to restraint system design (Shanahan and Shanahan, 1989b).

Figure 2. This seat became dislodged from its attachments with the pilot still strapped into it during the crash. His injuries were largely due his ejection during the crash.

Figure 3. The occupant of this seat was ejected when his lap belt detached from the seat.

In small aircraft with confined interiors (most helicopters), both lap belt and upper torso restraint are essential for crash survivability of crew and passengers. Not only does upper torso restraint reduce upper body flailing and contact with interior structures, but it also provides for greater distribution of acceleration loads across the body. A tie-down strap (crotch strap) incorporated into the restraint system helps reduce the potential for “submarining”. Submarining occurs when the lap belt rides up above the bony structure of the pelvis and compresses the soft organs of the abdomen. This frequently results in serious abdominal injury or spinal distraction fractures. Many so called "seat belt injuries” can be attributed to this mechanism. As an adjunct to standard belt type restraint systems, the U.S. Army is currently developing multi-bag, airbag systems for use in some of its helicopters (Alem et al., 1991). As in the automobile, these systems have tremendous potential for reducing the incidence of flailing injuries and should be economically adaptable to civil applications.

ENERGY ABSORPTION

Unlike transport category, fixed-wing aircraft, helicopters and light fixed-wing aircraft provide little crushable structure to attenuate crash forces. This is particularly true for the vertical direction ($+G_z$). Consequently, additional means of absorbing crash forces in the vertical direction frequently must be provided to prevent acceleration injury in potentially survivable crashes of helicopters. Kinematic studies of helicopter crashes have shown that the primary crash force vector is vertical in most survivable crashes (Shanahan and Shanahan, 1989a). Furthermore, depending on the type helicopter, vertical velocities maybe quite extreme (Shanahan and Shanahan, 1989a).

In general, there are three locations where vertical energy absorbing capability may be integrated into a helicopter design—the landing gear, floor structure, and the seats. The Black Hawk and Apache rely heavily on the fixed landing gear and seats to provide the required attenuation of loads for the 12.8 m/s (42 ft/s) design pulse. The landing gear alone were designed to handle over half of the total energy of a crash, with the floor and the seats absorbing the rest. This system has been proven extremely effective since fatalities are rare for vertical impacts up to approximately 15.2 m/s (50 ft/s) in these helicopters. The main disadvantage of this energy management system is that it is heavily dependent on having extended landing gear. Retractable gear helicopters should rely less on the gear and place more capability in the structure, although automatic emergency gear extension systems may prove to be effective. In mounting energy absorbing landing gear, it is important to do so in such a manner that the gear do not disrupt important structure or protrude into occupied areas after their energy absorbing capability has been expended.

Energy absorbing seats have been extremely effective in preventing acceleration injury in crashes with predominately vertical force vectors (Figure 3). Numerous designs are now available through a number of manufacturers. Experience with these seats in crashes has produced several lessons. First, it is essential that seats have adequate tie-down strength so that crash forces do not dislodge them. Second, designs that provide multi-axis stroking have not been as effective as those providing pure vertical stoking (Melvin and Alem, 1985). The increased head and torso strike zone tends to be far more disadvantageous than the minimal reduction in lateral and longitudinal accelerations provided by multi-axis designs. Third, the average load level for vertically stroking seats should not exceed 14-15G for military helicopters or 11-12G for civil helicopters (Coltman, VanIngen, and Smith, 1986; Shanahan, 1991; Singley, 1981). The different recommendation for military and civilian aircraft is based on differences in age and general health and, therefore, tolerance to impact, between the military and civilian populations. Finally, it is imperative that adequate stroke distance be provided to preclude “bottoming out" of the seat on structure since this situation results in extremely high acceleration spikes. As a point of interest, at least one manufacturer provides seats that have a variable-load energy absorber so that the seat may be adjusted to accommodate different weight occupants. This feature has considerable potential advantage where the weights of occupants vary significantly.

Figure 3. This seat stroked approximately 35.6 cm in a crash of a UH-60 with an estimated vertical impact velocity of 15.2 m/s. The pilot received no spinal injury.

LOCAL ENVIRONMENT

In designing an aircraft interior, it is extremely important to consider the local environment of the occupants at all potential seating locations (Figure 5). A person's local environment refers to the space that any portion of his body may occupy during dynamic crash conditions. Any object within that space may be considered an injury hazard. As an example, the cyclic and collective controls can pose a significant injury hazard to pilots during a crash, particularly when the visor on the flight helmet is not worn in the down position (Figures 6 and 7). The volume of that space will vary depending on the type restraint system anticipated and, to a lesser extent, on the anthropometry of the expected occupants. The maximum head strike distance is reduced by about 50 percent when upper torso restraint is utilized. Clearly, the primary concern must be for hazards within the strike zone of the head and upper torso, but objects within the strike zone of the extremities also should be considered.

Figure 5. The proximity of the cyclic and collective controls is aggravated by the stroking of the seats in the UH-60 as demonstrated by this subject in a seat stroked by a crash.

[redacted]

Figure 6. Note the shapes and locations of injuries to the left side of the face of this pilot.

Figure 7. Note how the switch guard and landing light adjustment switch correspond to the injuries of the pilot.

It is important to evaluate the local environment of occupants during the design phase of an aircraft since many potentially hazardous objects may be placed outside of the strike zone if they are recognized early in the design phase as hazards. In many cases placing hazardous objects outside of the strike zone is no more difficult or expensive than placing them within the strike zone. It is simply a matter of recognizing the hazard. Potentially injurious objects that cannot be relocated can be designed to be less hazardous, padded, or made frangible.

POSTCRASH FACTORS

Numerous aircraft accident victims survive the crash only to succumb to a postcrash hazard. These hazards include fire, fumes, fuel, oil, and water. Both civil and military crash experience has sadly shown that the most serious hazard to survival in helicopter crashes is fire. The design challenge is to provide for the escape of occupants after the crash under a host of adverse conditions. The approach may be either to control or eliminate the hazard at the source, to provide for more rapid egress, or a combination of both.

In the case of postcrash fire, controlling the hazard at the source has proven to be an extremely effective strategy for helicopters (Figures 8 and 9). Since the U.S. Army introduced crash resistant fuel systems (CRFS) into its helicopter fleet in the 1970's up to approximately 1997, there has only been one fire related death in a survivable crash (Shanahan and Shanahan, 1989b; Singley, 1981). Prior to the introduction of CRFS, up to 42 percent of deaths in survivable crashes of U.S. Army helicopters were attributed to fire (Haley, 1971; Singley, 1981). Considering the magnitude of the problem of postcrash fire in non-CRFS equipped helicopters and the incredible effectiveness of CRFS, it is most regrettable that helicopters continue to be produced without crash resistant fuel systems. This situation continues more because of the persistent failure of regulatory agencies to require CRFS use than that of the manufacturers to provide them. Indeed, many manufacturers have offered CRFS as an option, but few operators have opted to pay the additional cost, trusting instead that their helicopter will not be involved in a crash. Fortunately, significant progress now is being made in the regulatory arena. The U.S. Federal Aviation Administration has required CRFS fuel tanks in all newly certified helicopters since 1990, and at least one airframe manufacturer has incorporated CRFS into all airframes constructed since about 1982.

Figure 8. This is a severe crash of an AH-64. The fuel tank was ripped from the helicopter and found some distance from the wreckage.

Figure 9. Missing fuel cell from AH-64 shown in figure 8. The cell was found full without any evidence of leakage.

Other strategies employed to prevent the consequences of fire and fumes are to use fire retardant and low toxicity materials in the construction of aircraft and to provide physical separation of flammable materials from ignition sources and occupied areas.

For over-water operations, the most important postcrash hazard is generally the water itself. Because of their high center-of-mass, most helicopters rapidly invert and sink upon water entry whether the entry is controlled or uncontrolled. A high proportion of victims involved in water landings or crashes drown because they are unable to egress. Solutions to this problem have included use of helicopter flotation devices, improvements in interior emergency lighting, increased numbers of emergency exits, personal under-water breathing devices, and, most importantly, intensive under-water egress training programs.

IMPLEMENTING CRASHWORTHINESS

From the above discussion, it is apparent certain crashworthy features are more important than others in preventing injury in crashes. Although an integrated crashworthy design addressing the five basic factors is the most effective approach to reducing crash injury, significant improvements in crash survivability can be achieved through a more modest approach. This is particularly true for existing helicopters where it is usually not economically feasible to make extensive structural modifications. Frequently, relatively minor modifications such as replacing restraint systems or moving hazardous objects in the strike zone of occupants can prove highly effective. How does one rationally choose which features are more important than others? Accident statistics based on thorough investigations are useful for identifying the greatest hazards both in terms of frequency of occurrence and in terms of the seriousness of injuries caused by the identified hazard.

Most analysts agree that the greatest threat to life in helicopter crashes is postcrash fire (Bezreh, 1963; Department of Transportation, 1990; Haley and Hicks, 1975). The frequency of fire in otherwise survivable crashes and the overwhelming effectiveness of crash resistant fuel systems clearly dictate CRFS be considered the single most important crashworthy feature in a helicopter. It should be stressed that a fully crash resistant fuel system includes not only a crash resistant fuel cell but also breakaway, self-sealing fittings at critical locations in the fuel lines, automatic backflow shutoff valves in fuel vent lines, judicious placement of ignition sources and fuel lines, isolation of fuel sources from occupied spaces, and appropriately designed fuel diverters.

The choice of standards to apply in designing such a fuel system presents somewhat of a dilemma. The design standards specified in MIL-T-27422B have been proven extremely effective in preventing fire in all survivable crashes of U.S. Army helicopters (Department of Defense, 1971; Shanahan and Shanahan, 1989b; Singley, 1981). However, exclusive of the ballistic requirements, these standards are considered by many to be excessive for civil helicopter operations. This perception lead to the development of the reduced standards specified in the current FAA standards for CRFS (Department of Transportation, 1990). Numerous civil helicopters have been equipped with fuel systems designed essentially to these standards, and preliminary results from crashes indicate that these systems may be reasonably effective at reducing post-crash fires, at least for light helicopters with high inertia rotor systems. These standards may prove less adequate for transport category helicopters and smaller helicopters with low inertia rotor systems due to their tendency to crash at higher sink rates (Shanahan and Shanahan, 1989a). Time and additional crash experience most certainly will clarify this issue.

The second most serious injury hazard in helicopter crashes is contact injury. Since these injuries are due to a variety of mechanisms, the solution to the problem is considerably less straightforward than in the previous example. Probably the most important factor to consider in modifying existing helicopters is occupant restraint. Seats and restraint systems should, as an absolute minimum, meet the retention standards specified in the current Federal Aviation Regulations Part 27 (Department of Transportation, 1992). In most helicopters, it would be advisable to increase these standards by a factor of 1.5-2.0. Cockpit seats should be equipped with five-point restraint harnesses and all passenger seats should have four- or five-point harnesses. Lap belt only restraint should be considered inadequate for any occupant position. Potentially hazardous internal items such as a fire extinguisher and first-aid kits also should be adequately restrained and moved from potential strike zones or padded. There is no rational justification for using lesser standards for internal object retention than those applied to occupant retention.

Of almost equal importance in preventing contact injury in helicopter crashes is strength of the container. Contact injury is due to relative motion between the occupant and potentially injurious structures. Occupant motion can be controlled with well-designed restraint systems, but if structure collapses onto occupants, the effectiveness of occupant restraint becomes relatively unimportant. Fortunately, structural collapse is not a consideration in all crashes, whereas occupant restraint is. Also, it is difficult, and frequently prohibitively expensive, to increase structural strength through a retrofit program. For this reason, occupant restraint is emphasized over structural integrity issues when considering modification of existing airframes. Nevertheless, one should remember that the properly restrained human is capable of withstanding accelerations exceeding 40G without sustaining serious injury, and a container designed to a lesser standard will, under survivable crash conditions, compromise occupant survival. Consequently, in newly designed helicopters, structural strength and occupant restraint should receive equal consideration. Design compromises in this area should be made with a clear understanding of the expected crash environment for the helicopter under design as well as with an understanding of crash injury mechanisms and human tolerance to impact. In general, container strength or restraint integrity should not be the limiting factor in occupant survival.

A final consideration in preventing contact injury is high mass item retention. Current FAA standards for high mass item retention such as transmissions and engines are extremely low (Department of Transportation, 1992). Although a relatively infrequent hazard, intrusion of these components into occupied spaces frequently has tragic consequences. The results are particularly vivid when rotor systems penetrate the cockpit. When appropriate consideration is given to the placement of these items with respect to occupied spaces and to their tie-down strength to the airframe, intrusion of these items can be practically eliminated as a hazard in survivable crashes (Shanahan and Shanahan, 198933; Singley, 1981). Current FAA retention standards should be increased by a factor of at least 2.0.

The last type of injury to consider is acceleration injury. Pure acceleration injuries are relatively uncommon in helicopters with well-designed conventional seating systems, except at the extremes of the crash survivability envelope. The most common acceleration injury seen in helicopter crashes is spinal compression fracture that may occur at 25-30G, in young to middle aged adults. Only a small portion of potentially survivable crashes exceed 30G at the floor, and a properly designed seat should prevent the occupant from experiencing loads significantly in excess of this value. However, poorly designed seats can produce spinal fracture in impacts as low as 8-10G. Typically, spinal fractures in low to moderate velocity crashes are caused by mounting seats above rigid panels or other non-frangible objects such as batteries and from mounting relatively rigid seats directly on bulkheads or over beams. In the first case, seats collapse onto unyielding objects causing the occupants to experience excessive vertical accelerations. In the later case, rigid bulkheads or structural members transmit excessive forces from the ground directly to the seat occupants.

To prevent acceleration injuries over the range of survivable impacts, all helicopters should be equipped with energy absorbing seats. Federal Aviation Regulations Parts 27 and 29 specify dynamic testing requirements for seats in newly certificated helicopters (Department of Transportation, 1992). These requirements are adequate for light helicopters, particularly those with relatively high inertia rotor systems. However, for larger helicopters and those with low inertia rotor systems, one should consider using the more rigorous requirements specified in MIL-S-58095A (Department of Defense, 1988). Experience with the UH-60 and AH-64 suggests that large helicopters with low inertia rotor systems will crash at much higher vertical velocities than previously anticipated. These high sink rate crashes require significantly better load attenuation in the seats than specified in the FAA requirements to provide protection against spinal injury. A less crashworthy seat in either of these helicopters would have resulted in an unacceptable injury rate in potentially survivable crashes (Shanahan, 1991; Shanahan and Shanahan, 1989b).

In summary, the seating system in an aircraft must be viewed as part of the overall energy management system in a crash. The degree of capability built into the seat should be based upon an assessment of the projected or known crash environment and the load attenuation capability of the under floor structure and landing gear. Above all else, designs that permit bottoming out on non-frangible structure in a potentially survivable crash should be avoided.

CONCLUSIONS

Crashworthiness is not inherent in most aircraft designs since features that enhance crash performance do not usually improve operational performance or efficiency. There is usually a cost associated with crashworthy enhancements to an airframe. This cost may be expressed in increased base price, decreased performance, increased weight, or a combination of the above. The latter three factors trans-late into increased operating cost. Counterbalancing these factors are the two major benefits provided by a crashworthy aircraft. First, crashworthiness results in reduced injury in crashes and, second, enhanced airframe crashworthiness frequently reduces repair costs or renders what would otherwise have been a destroyed airframe repairable after relatively low velocity impacts. For example, the Black Hawk and Apache have demonstrated their ability to absorb hard landing impacts of up to 6.1 m/s (20 ft/s) with minimal or no damage to the aircraft and no injury to their occupants. For most other helicopters, similar impacts would have resulted in a destroyed airframe and the potential for serious injury to the occupants.

Considering these factors, the degree of crashworthiness incorporated into any helicopter design will always involve trade-offs between the perceived risk of a crash and increased cost. Unfortunately, in this assessment, the risk of a crash tends to be grossly overoptimistic, particularly when made by individuals responsible for managing development costs. This is equally true for the civil and military communities. As with most advancements in safety, significant advancements in crashworthiness are not likely to be made unless required by regulation. The challenge for regulators is to establish realistic crashworthiness standards that will be effective yet not cost prohibitive. For instance, it would be unreasonable to impose the complete U.S. Army crashworthy standards on civil helicopters of less than 10,000 pounds gross weight (Shanahan and Shanahan, 1989a and 1989b). Nevertheless, certain portions of the Army standards would be beneficial for all helicopters. The challenge to design engineers is to implement the standards through designs that minimize costs while maximizing effectiveness.

Appropriate standards can only be established and revised through a program of detailed accident investigation where injury causation and aircraft impact parameters are investigated and documented as thoroughly as accident causation factors. This is a glaring deficiency of most agencies charged with the investigation of aircraft crashes today, and it explains why few accident data bases contain sufficient information upon which to develop realistic crashworthy standards. This is a problem that needs to be addressed by users, manufacturers, industry organizations, investigation agencies, and regulators alike.

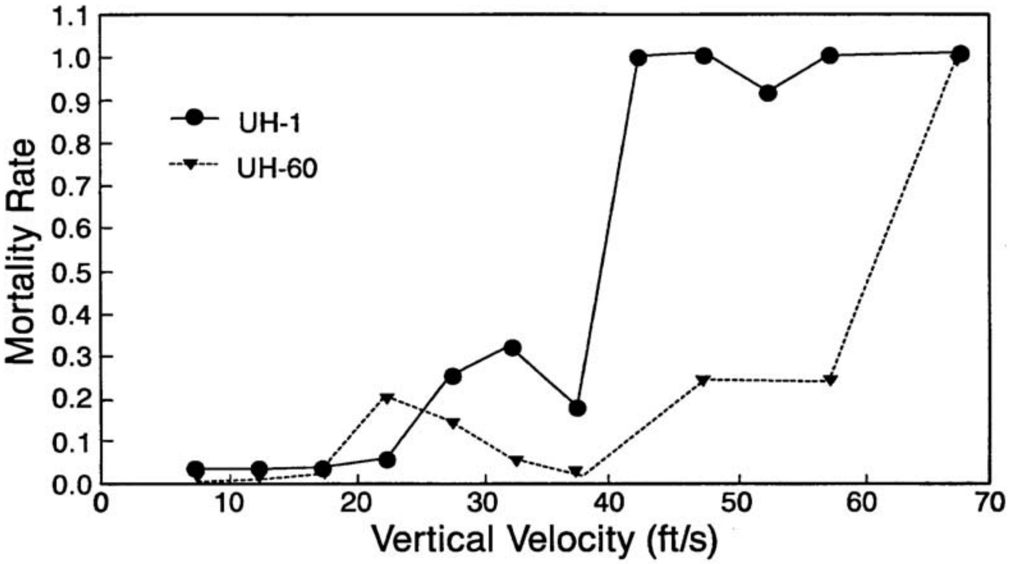

Figure 10. Cumulative frequency plot of mortality rate versus vertical impact velocity for the UH-1 and UH-60.

The bottom line is that crashworthiness works. Figure 10 is derived from a publication comparing injury rates in a conventionally designed helicopter (UH-1) with a crashworthy helicopter (UH-60) (Shanahan, 1992). This graph plots mortality rate against vertical velocity at impact for both types. The mortality rate was calculated at 5 ft/s intervals of vertical impact velocity for each helicopter type and plotted on the graph. Mortality rate was calculated by determining the number of fatalities occurring within each increment of vertical velocity and dividing by the total number of occupants exposed to impacts with vertical velocities within the increment. Notice that both curves demonstrate a threshold velocity above which mortality essentially becomes one hundred percent. This threshold occurs in the UH-1 at a vertical velocity of approximately12.2m/s (40 ft/s) and in the UH-60 at about 18.3 m/s (60 ft/s). Clearly, the UH-60 is able to provide protection to its occupants in considerably more severe crashes than the conventionally designed UH-1.

The technology is currently available to vastly increase the crashworthiness of the civil and military helicopter fleet worldwide. What is lacking is commitment and the allocation of necessary resources. If the true cost to society of injury incurred in helicopter crashes were properly assessed, it would clearly show that a long-term commitment to crash survivability would, in fact, be cost effective.

REFERENCES

Alem, N.A., Shanahan, D.F., Barson, J., and Muzzy, W. 1991. The airbag as a supplement to standard restraint systems in the AH-1 and AH-64 attack helicopters and its role in reducing head strikes of the copilot/gunner. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory, USAARL Report No.91-6.

Bezreh, A.A. 1963. “Helicopter versus fixed wing crash injuries,” Aerospace medicine, 34(1): 11-14.

Carnell, B.L. 1978. Crash survivability of the UH-60A helicopter. Operational helicopter aviation medicine, Neuilly-sur-Seine, France: AGARD CP 255, 1978, pp. 64-l to 64-10.

Coltman, J.W., Van Ingen, C., and Smith, K. 1986. Crashworthy crew seat limit load optimization through dynamic testing, Crashworthy design of rotorcraft Atlanta: Georgia Institute of Technology Center of Excellence for Rotary-Wing Air-craft Technology.

DeHaven, H. 1969. Beginnings of Crash Injury Research, Proceedings of the 13th Stapp Car Crash Conference. Detroit: Society of Automotive Engineers.

Department of the Army. 1989. Aircraft crash survival design guide. Fort Eustis, VA: Aviation Applied Technology Directorate, U.S. Army Aviation Systems Command (USAAVSCOM), TR 89-D-22.

Department of Defense. 1984. Light fixed- and rotary-wing crashworthiness. Washington, DC: Department of Defense, MIL-STD-129OA (Av).

Department of Defense. 1971. Military specification. Tank, fuel, crash resistant, aircraft. Washington, DC: Department of Defense, MIL-T-27422B.

Department of Defense. 1988. Seat system: Crashworthy, non-ejection, aircrew, general specifications for. Washington, DC: Department of Defense, MIL-S-58095A (AV).

Department of Transportation. 1992. Federal Aviation Administration: Airworthiness standards: normal and transport category rotorcraft. Washington, DC: Department of Transportation, 14 CFR Parts 27 and 29.

Department of Transportation. 1990. Federal Aviation Administration: Airworthiness standards; crash resistant fuel systems in normal and transport category rotorcraft. Washington DC: Federal Aviation Administration, NPRM-41000, Notice No. 90-24, October.

Haley, J.L., Jr. 1971. Analysis of U.S. Army helicopter accidents to define impact injury problems, Linear acceleration of the impact type, Neuilly-sur-Seine, France: AGARD CP 88-71, pp. 9-l to 9-12.

Haley, J.L., Jr., and Hicks, J.E. 1975. Crashworthiness versus cost: A study of Army rotary-wing aircraft accidents in the period Jan 70 through Dee 71, Aircraft Crashworthiness, Saczalski K., et al. (eds.), Charlottesville, VA: University Press of Virginia.

Hicks, J.E., Adams, B.A., and Shanahan, D.F. 1982. Analysis of U.S. Army mishap patterns, Impact injury caused by linear acceleration: Mechanisms, prevention and cost, Neuilly-sur-Seine, France: AGARD CP 322, 1982, pp. 34-l to 34-12.

Mattox, K.L. 1968. Injury experience in Army helicopter accidents, Fort Rucker, AL: U.S. Army Board for Aviation Accident Research, HF 68-l.

Melvin, J.W., and Alem, N.M. 1985. Analysis of impact data from a series of UH-60 'Black Hawk' pilot seat tests, Columbus: Battelle Columbus Laboratories.

Sand, L D. 1978. Comparative injury patterns in U.S Army helicopters, Operational helicopter aviation medicine, Neuilly-sur-Seine, France: AGARD CP 255, pp. 54-l to 44-7.

Shanahan, D.F. 1992. Crash experience of the U.S. Army Black Hawk helicopters. Aircraft accidents: Trends in aerospace medical investigation techniques. Neuilly-sur-Seine, France: AGARD CP 532, pp 40-l - 40-9.

Shanahan, D.F. 1991. Black Hawk crew seats: A comparison of two designs. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory, LR 92-1-4-1.

Shanahan, D.F., and Shanahan, M.O. 1989a. Kinematics of U.S. Army helicopter crashes 1980-1985, Aviation, space, and environmental medicine, 60:112-121.

Shanahan, D.F., and Shanahan, M.O. 1989b. Injury in U.S. Army helicopter crashes October 1979-September 1985, Journal of trauma, 29(4): 415-423.

Singley, G.T., III. 1981. Aircraft occupant crash-impact protection, 22(4): 10-12. Army R, D & A.

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14. Abstract

The development of effective crashworthiness design and design criteria, personal protective equipment and in-flight escape systems depends on obtaining accurate injury data from aircraft crashes and ejection. The depth and quality of injury data collected by member nations is sporadic and usually lacking in the determination of the injury mechanism.

In this LS, we have reviewed several aspects of the Aircraft Accident Investigation we think are key for the investigator. We have put especial attention to aspects related to the role of the FS and Investigator, how to behaviour in the crash site, what data should be collected and how to proceed in relation to the analysis of the injuries.

In this perspective we put together the methodology that it should be apply and the structured procedures to identify and to evaluate the underlying causes in order to prevent new similar events.

Also it has been presented a deep review of mechanism of injuries, how we analyse them and how they might be scored and be able to identify patterns of injury as a viable tool for accident reconstruction.

In addition to that incapacitation events were presented and detailed information provided.

Also toxicological and pathological findings related to the material to be investigated and the post-mortem diagnosis were explained and the appropriate interpretation used as a particularly remarkable evidence for further clarification of the correct sequence of events.

Finally human tolerance and crash survivability has been explained and basic principles of crashworthiness and crashworthy design by using the CREEP model extensively discussed.

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