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An analysis of brain injuries in 268 ejection seat aircraft ejections: the prevalence of loss of consciousness and helmet design implications

Alasdair Iain Mackay[a,b], Xiancheng Yu[c], Matthew Elfed Lewis[b]

[a]Dyson School of Design Engineering, Imperial College London, UK

[b]Royal Air Force Centre of Aerospace Medicine, Henlow, Bedfordshire, UK

[c]School of Mechanical, Aerospace and Civil Engineering, University of Sheffield, UK

Corresponding author: Alasdair Iain Mackay, Alasdair.Mackay2@nhs.net +443301616574

Abstract

Introduction

Ejections from combat aircraft pose a significant risk of head injury, and the primary protective measure against such injuries is the aircrew helmet. Internationally, aircrew helmets are typically certified against motorcycle or motorcycle-derived helmet standards, which may not reflect the injury mechanisms experienced during aircraft ejections.

Methods

The objective of this study was to identify the historical risk of head injury associated with combat aircraft ejections. All UK combat aircraft ejections from 1972 to 2025 were analysed to determine common brain pathologies, head injury mechanisms and helmet damage characteristics.

Results

In total, 268 aircraft ejections were recorded, with 12% resulting in a head injury. Two primary head injury mechanisms were identified: headbox impact (58%) and parachute landing (27%). The findings indicate that aircrew helmets provide protection against skull fracture, as no cases were recorded following in-envelope ejections. This outcome is likely attributable to existing aircrew helmet standards, which assess helmet performance based on peak translational acceleration, a parameter closely linked to skull fracture. A key finding is that loss of consciousness associated with head rotation was the most prevalent pathology, comprising 76% of all head injuries.

Conclusions

These results inform potential improvements in aircrew helmet standards. Even a brief incapacitation, such as a loss of consciousness, can impair aircrew escape and evasion capabilities, thereby affecting survivability. Consequently, this study recommends that future aircrew helmet standards expand their test methods to include assessments of rotational injury, with the aim of mitigating the risk of loss of consciousness.

Key messages

What is already known on this topic

- Aircrew ejection exposes occupants to violent accelerations, windblast and environmental stressors, and clinically significant head injuries are recognised as a common consequence.
- Military aircrew helmet standards are largely derived from legacy motorcycle helmet standards and are designed primarily to limit linear head acceleration, with limited consideration of the specific head impact conditions that occur during ejection.

What this study adds

- In 268 UK combat aircraft ejections, 12% resulted in head injury, with loss of consciousness the predominant brain injury and no deaths or skull fractures for in-envelope ejections.
- Seat headbox impact ("slamback") and parachute landing accounted for all in-envelope head injuries, with damage concentrated over the rear and sides of the helmet and head injury risk increasing with aircraft speed at ejection.

How this study might affect research, practice or policy

- These findings will underpin the updated Military Aircrew Helmet Impact Standard (MAHIS), which will incorporate rotational head kinematics and injury criteria related to loss of consciousness.

Introduction

Combat aircraft equipped with ejection seats often operate at low altitudes and in contested airspace, where hostile threats or mechanical failures may necessitate urgent escape. Once the decision is made to eject, the occupant is rapidly propelled from the cockpit by the ejection seat. This process is necessarily violent, exposing the individual to high whole-body accelerations and environmental stressors, including windblast and hypobaric atmospheric conditions.[1] As a result, injuries from mechanical trauma are not uncommon and frequently involve the head.[2-4]

A key system for reducing the risk of head injury is the helmet, which is primarily designed for impact protection but also serves as a platform for essential aircrew equipment, such as oxygen masks, night vision goggles, and integrated helmet-mounted displays. Military aircrew helmets consist of a hard outer shell and an expanded polystyrene liner (EPS) (Figure 1). The EPS liner crushes on direct impact, effectively absorbing translational (linear) acceleration. However, it is not optimised for reducing rotational acceleration.[5-7]

Figure 1(a) Mk 10 UK aircrew helmet (b) Mk10 cross section. Image 1a courtesy of Gentex Europe.

In the UK, aircrew helmets are tested to Defence Standard 05-102, commonly referred to as the Military Aircrew Helmet Impact Standard (MAHIS).[8] This standard is based on the BS6658:1985 motorcycle helmet standard, and it has been updated with data from a review of European motorcycle helmet accident data as well as damage replication studies.[8-10] Helmets are mounted on a steel headform and impacted against a flat or hemispherical anvil, with a pass/fail threshold of 300 g. Helmets are first impacted at 6 m/s, followed by a second impact at 4.3 m/s at the same location, targeting the front, rear, side, and crown of the helmet. Internationally, similar standards are employed, with most military aircrew helmets tested against motorcycle or motorcycle-derived requirements.

However, the head impact conditions and resulting brain injuries for aircrew can differ significantly from those experienced by motorcyclists. Only through understanding the specific head injury risks during ejection can more appropriate test methods be developed, ultimately guiding the design of effective and optimized head injury mitigation strategies. However, there are currently no published data quantifying the head injury risks associated with each stage of the ejection sequence.

The aim of this study is to determine the incidence, mechanism, and type of head injury sustained by aircrew during ejection. A unique database of 268 ejections was analysed to identify the common injury mechanisms and head impact conditions experienced during ejections and the resulting pathologies.

Methodology

The ejection database

Physical records of ejections from 1972 to 2025, collected by the Accident Investigation and Human Factors department of the Royal Air Force Centre of Aerospace Medicine (RAFCAM), were reviewed for this study. The records consisted of paper-based documentation from the initial medical review, subsequent assessments by Aviation Medicine physicians, reports from safety equipment fitters, and, where available, imaging and post-mortem reports.

Head injuries

All head injuries sustained during ejection were recorded. Superficial abrasions and bruises were excluded, as they are unlikely to affect post-ejection survival or escape and evasion.

Helmets

High-resolution photographs of the helmets were used to identify the impact location and the likely impact surface. Impact locations were classified as front, side, crown, or rear.[11]

Ejection parameters

Ejections were categorised as either in-envelope (IEE) or out-of-envelope (OEE). The ejection envelope defines the limit of an ejection seat to be able to operate effectively and is based on factors such as aircraft speed, altitude, attitude, and occupant mass.

Additional data recorded included the aircraft type and indicated air speed (IAS).

Statistical analysis

Shapiro–Wilk normality tests were used to assess the distribution of IAS for the head-injury, non-head-injury, IEE, and OEE groups. Because the OEE injury group did not follow a normal distribution, a Mann–Whitney U test was employed to compare IAS between the two groups. Simple logistic regression was used to analyse the relationship between IAS and the risk of head injury. Multiple logistic regression was then conducted to assess the relationship between aircraft type and the presence of head injury, correcting for IAS as well as the interaction between aircraft type and IAS. Relative risk (RR) was calculated for each aircraft type, using the aircraft with the lowest risk as the reference. RStudio version 2024.12.0 was used for these analyses.

Ethics statement

The study used anonymised data from the Royal Air Force Centre for Aerospace Medicine ejection database and did not require formal research ethics committee approval or individual informed consent. This study does not involve human participants.

Results

268 UK combat aircraft ejections were recorded in the accident database. 12% (33/268) involved head injuries. Of these cases, 73% (24/33) were classified as IEE, and 27% (9/33) were OEE. Further details of these ejections can be found in the Supplemental Table.

Loss of consciousness the dominant brain injury

Loss of consciousness (LOC) was the most prevalent brain injury documented in the database, occurring in 79% (26/33) of head injury cases. 27% (7/26) involved an LOC of five minutes or more, with the longest recorded duration 25-30 minutes. All remaining episodes lasted less than five minutes.

Among IEE cases with head injury, LOC occurred in 96% (23/24) of cases (Figure 2). The remaining IEE case involved a single episode of concussion without loss of consciousness, described as confusion and disorientation.

Within OEE cases with head injury, 67% (6/9) were fatal (Appendix A). All fatal cases involved catastrophic, unsurvivable head injuries, resulting from mechanical forces beyond the reasonable protective capacity of a helmet such as complete head fragmentation.

Figure 2 Injury analysis of 268 UK ejections. IEE = in-envelope ejection, OEE = out-of-envelope ejection. LOC = loss of consciousness, concussion = concussive symptoms without a LOC, SAH = subarachnoid haemorrhage, fragmentation = complete disruption of the skull vault and brain tissue, BSF = basilar skull fracture.

Headbox impact is the main cause of head injury

For IEE, the dominant cause of head injury was the impact between the helmeted head and the ejection seat headbox, also called “slamback”, accounting for 79% (19/24) of head-injuries, all of which involved LOC. The second most common cause was ground impact during parachute landing, responsible for 17% (4/24) of head injuries. Together, these two mechanisms explained 23 of the 24 head injuries in IEE cases. The remaining case involved windblast at 462 kts, with no clear evidence of helmet impact against the headbox or ground.

In out-of-envelope ejections (OEE), the mechanisms of injury were more diverse, including impacts with aircraft structures, crush injuries, and ground impact while the occupant was still attached to the ejection seat.

Higher risk of head injuries in Tornado aircraft

The risk of head injury per ejection varied according to aircraft type. Excluding Canberra, Tucano, and F-35 ejections, which were too few to draw robust conclusions, Tornado ejections showed the highest risk at 17% (18/104), followed by Hawk at 12% (4/47), Jaguar at 7% (3/41), and Harrier at 4% (3/71) (Figure 3). Jaguar, Hawk, and Tornado ejections were 2.05, 2.44, and 4.47 times more likely, respectively, to result in a head injury when compared with Harrier ejections.

Figure 3 Number of ejections and head injuries by aircraft type.

Higher air speed at ejection increased the risk of head injuries

Information about indicated air speed (IAS) at the time of ejection was available for 87% (234/268) of recorded ejections, which included all ejections in which a head injury occurred. The IAS for ejections resulting in head injury was higher than those without a head injury (310 ± 136 kts vs 254 ± 128 kts; $W = 2169$, $p < 0.01$). A logistic regression examining the relationship between IAS and the likelihood of a head injury showed a statistically significant positive association (Est = 0.005, SE = 0.002, $z = 3.07$, $p < 0.01$). The risk of sustaining a head injury increased by 0.5% for every additional knot of aircraft speed (95% CI [0.002, 0.008]). Multiple logistic regression did not find a significant effect of aircraft type, nor an interaction between aircraft type and IAS, on the risk of head injury.

Helmet impact damage concentrated in the rear and side regions

21% (55/268) of ejections resulted in damage to the helmet outer shell. The most common areas of damage were the rear (42%) and side (36%) of the helmet, with fewer impacts occurring on the front and crown (Figure 4a). There was no evidence of damage to the shell covering the earcups.

93% (51/55) of the helmets indicated an impact with a flat surface. Only 7% (4/55) helmets had linear witness marks on the helmet shell (e.g. Figure 4b), indicating impact with an edge. No instances of penetrating damage were identified.

There was no indication of multiple impacts to the same area of the helmet, such as overlapping linear witness marks or a combination of linear and flat impact damage in the same location.

Figure 4 Helmet damage patterns. (a) Damage locations grouped by MAHIS test zones. (b) Linear witness mark on the left-rear shell; red arrows indicate the medial and lateral extent of the damage.

Discussion

We found that the primary brain injury reported in aircrew in-envelop ejection is loss of consciousness (LOC). We also found that the dominant mechanism of this injury is headbox impact. These results are based on using an in-depth ejections database maintained at the Royal Air Force Centre for Aerospace Medicine, which uniquely includes information on all UK ejection events since 1972, totalling 268 ejections. The database contains details about the mechanism and severity of any injuries and a thorough analysis of all protective equipment worn, which were crucial for this study. This study builds the evidence base for improving military aircrew helmet impact standards, which are currently based on motorcycle helmet standards. More specifically, the results demonstrate that future aircrew helmet standards should expand their assessments to include protection against LOC.

There are several regions within the brainstem that are associated with consciousness, specifically arousal. Pathology in these regions has been shown to cause disorders of consciousness.[12] Recent research on sporting collisions has shown that the level of mechanical strain and strain rate produced at nuclei within these regions is associated with a transient loss of consciousness.[13] This implies that helmet design should be improved to reduce loading of brainstem to reduce risk of LOC.

Several studies have shown that brain tissue strain and strain rate are closely associated with rotational kinematics of the head.[13-16] However, current aircrew helmet requirements in the UK and internationally do not explicitly require demonstration of protection against rotational loading. In contrast, the findings here suggest that contemporary aircrew helmets provide protection against injury mechanisms associated with translational loading, such as skull fracture. Evidence of multiple impact events was apparent from the pattern of helmet damage, consistent with head contact against surrounding structures during ejection. Despite this, no skull fractures were recorded following in-envelope ejections in this dataset, suggesting that impact loads were attenuated to below fracture thresholds under the ejection conditions examined.[17]

This study shows that current aircrew helmets do not adequately address pathologies linked to rotational head kinematics, such as LOC. Therefore, it is recommended that future aircrew helmet impact standards include an assessment of helmets' ability to protect against rotational loading, given its relevance to the risk of incapacitation.

Headbox impact was the most prevalent head injury mechanism during in-envelop ejection, resulting in LOC in all head injury cases. Once the ejection seat pan handle is pulled, the seat begins accelerating the aircrew out of the cockpit (Figure 5a). The resultant force causes the head to slump toward the chest, increasing the distance between the head and the ejection seat headbox. As the individual leaves the cockpit, they are exposed to "windblast." At high aircraft speeds, this can propel the head backward against the ejection seat headbox. We found a positive relationship between airspeed and the likelihood of head injuries. Higher aircraft speed can increase the speed at which the helmeted head strikes the headbox, thereby elevating both linear and rotational head kinematics and raising the risk of injury.

The second prevalent mechanism was parachute landing (Figure 5b). The ejection seat headbox contains a parachute that is released once the seat leaves the aircraft cockpit. As the parachute inflates, the ejection seat detaches, allowing the aircrew to descend to the ground. The rate of descent depends on factors such as the type of parachute, aircraft altitude, attitude, speed at ejection, and the occupant's weight. Because the parachute offers only limited steering capabilities, the aircrew has little influence over the landing site, and head impacts can occur on various surfaces during landing.

Figure 5 Ejection seat aircraft head injury mechanisms. (a) Headbox "slamback", and (b) Parachute landing. Image courtesy of Martin-Baker Aircraft Company

The most common impact surface identified from helmet witness marks was flat, which supports the use of flat anvils in laboratory test methods. However, the number of non-flat impacts may be underestimated because of the widespread superficial damage often observed on helmets after ejection. All helmet impacts against non-flat surfaces resulted from the helmet contacting the edge of the ejection seat headbox. An "edge" type, known as a kerbstone anvil, would more closely replicate this interaction than the hemispherical anvil currently used for non-flat impacts.

No evidence of penetrating injuries was found in any of the ejections. This may be due to early efforts in aircraft design to restrain aircrew effectively and "de-lethalise" cockpits by removing or modifying objects that could cause penetrating injury during the ejection sequence.[1] Although it is possible that aircrew could strike a sharp object on parachute landing, such objects are relatively uncommon in natural settings. Consequently, this research does not support introducing a penetration-resistance test in future helmet standards.

All zones of the helmet, including front, side, rear, and crown, were shown to sustain impacts, though 78% of recorded impacts occurred on the rear and side. Helmet slamback likely explains this high proportion. While the absence of damage does not rule out an impact, the presence of damage is a clear sign of impact that has been large enough to produce visible damage. Our results indicate the importance of protection in all zones, particularly rear and side. We did not find evidence to support adding an impact test for the earcup region in helmets used in ejection seat aircraft, despite this location being tested in the US Department of the Interior civilian aircrew helmet standard.[18]

There was no evidence of a second impact in the same location during ejections. It is possible that aircrew could strike the back of their helmet during slamback and then land on the same site, though this sequence was not identified in any of the analysed cases. Adding a second impact requirement at the same location in test methods, e.g. MAHIS, would likely increase helmet stiffness and shell thickness. Greater stiffness may reduce protection for milder injuries such as LOC,[19] and a heavier shell can increase the risk of chronic neck pain.[20]

Limitations

In this study, helmet damage was identified by visual inspection of the helmet shell and liner and in some cases, it was examined using plain film X-rays. More advanced techniques, such as CT scans and electron microscopy, may have detected additional cases of significant helmet impacts that were not identified during initial assessments, though these technologies were less readily available than they are today.

Most cases of LOC were determined clinically, based on the history provided by the aircrew after ejection. UK aircrew are not routinely filmed inside the cockpit, and there is no physiological monitoring of their conscious state during the ejection sequence. Consequently, some instances of LOC may have been overlooked, or aircrew recollections may be inaccurate. To improve diagnostic specificity, only cases recorded as LOC by the investigating physician were included, which reduced the potential for subjective error.

Conclusions

In summary, this study found that across the dataset, 12% of ejections resulted in a head injury; however, among in-envelope ejections there were no deaths and no skull fractures.

Where head injury did occur, loss of consciousness was common, and in in-envelope ejections it was the only brain injury described. Helmet inspection showed that damage most often affected the rear and lateral aspects, with no evidence that the same site sustained multiple impacts. Flat damage was the predominant pattern in in-envelope ejections, identified in 21 cases, whereas linear impact marks were uncommon (three cases).

A key recommendation based on this work is that rotational kinematics of the headform should be monitored in impact tests to assess the protection of aircrew helmets against LOC. Given the high risks associated with post-crash fires, ejection over bodies of water, and other hostile environments, it is vital to identify and mitigate the risk of LOC. The improved test methods will encourage novel helmet designs that protect against a wider range of brain injuries.

Competing Interests Statement

No competing interests.

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