Qualification Criteria for Neck Loads in Windblast Testing of Aircrew Helmet

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Abstract

The Institute is involved in providing aeromedical consultancy to Indian certification agencies during integration of 'off-the-shelf' aircrew equipment assemblies with existing aircraft. Helmet Mounted Displays (HMDs) have been recently introduced in the IAF and are in the process of integration with a number of aircraft. Increased neck loads due to HMDs occur due to an increased overall weight as well as weight distribution as compared to standard helmets. In this case, there is a greater risk of cervical injury during ejection from high speed fighter aircraft.

This paper discusses the legacy criteria as laid down in AGARD AR 330 and the subsequent attempts at developing neck loads criteria like the Nij criteria, Lower Neck Beam criteria, Neck Injury Criteria (NIC), Knox box and others with their associated drawbacks and problems of applying in the aviation environment. The advantages and limitations of the new Multi-Axial Neck Injury Criteria (MANIC) developed by the US Air Force is discussed thereafter. The multi-axial nature of the MANIC which is more holistic and physiologically scientific in nature as compared to the previous criteria is brought out. The greatest strength of the MANIC criteria is the data-based injury risk probability curves that can be used to quantify the risk and severity of neck injury. This paper recommends use of MANIC as the Qualification Criteria for neck loads during wind blast testing of helmet and helmet mounted devices.

Keywords: Neck Injury, Windblast tests, HMD, MANIC.

Introduction

Institute of Aerospace Medicine provides subject matter expert consultancy to the Aerospace Industry on aeromedical standards of various aircrew clothing and flight safety equipment. The Institute is also involved in providing aeromedical consultancy to Indian certification agencies during integration of 'off-the-shelf' aircrew equipment assemblies with existing aircraft.

In the last two decades, Helmet Mounted Displays (HMDs) have been integrated or are proposed for integration in some new and some older IAF aircrafts. While adding to performance of operators and overall mission effectiveness, these HMDs pose a greater threat of injury to the aircrew neck during ejection as compared to the lighter standard flight helmet [1–6]. During ejection, traditionally, the risk of injury and therefore the loads have been studied on the lumbar spine. In the changing scenario of increased use of head mounted devices, concerns of loads solely on the lumbar spine of the aircrew during the catapult phase of ejection do not suffice anymore.

<u>Neck loads due to HMDs</u>. Increased neck loads due to HMDs occur due to an increased overall weight as well as weight distribution as compared to standard helmets. The risk of chronic neck injury may be due to higher loads during routine flying. However, the potentially more severe risk is during ejection. This may be of various severity; from strains and muscle tears to cervical spine fractures and spinal cord damage.

Such injury is likely to occur at two phases of the ejection sequence. The first is during the catapult phase of ejection where the primary force is compressive along the axis of the spine including a rotational moment forward and downwards. This is a function of the overall weight and weight distribution (CoG) of the helmet. The second phase when injury may occur is during the windblast phase of ejection where the primary force is tensile or distraction along the axis of the cervical spine including a rotational moment which is backwards and upwards [Fig 1].

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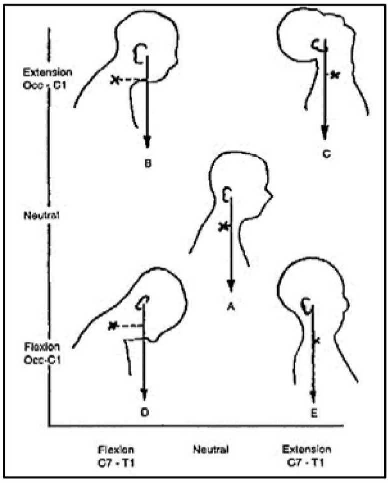

Fig 1. Forces acting on the cervical spine.
Ref.: - Burton R. RTO TR Report - 4. Cervical Spinal Injury from Repeated Exposure to sustained acceleration. 1999.

Testing for Neck Injury potential.

The risk of neck injury is evaluated by carrying out ejection tests for the catapult phase, windblast tests for the windblast phase and rocket sled tests for the dynamic combined effect of complete ejection forces. However, often the ejection tests and the windblast tests are carried out alone. This necessitates the use of qualifying criteria for the same. These criteria have been traditionally derived from existing road transport crash data to a large extent. Some of these criteria have been uniaxial or multiaxial in nature. Some of these criteria plot tolerable forces against the duration of application of force, while some consider peak instantaneous forces only. Some of these criteria quantify the probability of injury to various extents. Some criteria have quantified the severity of risk. Few of these criteria provide injury risk probability curves for different severity of injury.

Legacy criteria/ standards

IAM has followed the existing criteria for cervical injury as laid down in AGARD AR 330. Since then, there have been subsequent attempts at developing improved neck loads criteria like the Nij criteria, Lower Neck Beam criteria, Neck Injury Criteria (NIC), Knox box amongst others. Each of the criterion as mentioned above suffer from certain limitations. A brief description of the criteria is given below: -

(a) Mertz Criteria. Mertz HJ et al described two injury reference curves for axial compressive neck loading based on measurements made with Hybrid III dummy [7]. However, due to limited information relating to neck loadings measured with the Hybrid III dummy known, these injury references could only be used as guides. Neck injuries that result from bending, shearing, axial tension or combination of these loadings are not applicable to either of the two axial compressive force referenced in this study.

(b) AGARD AR 330 [8]. These criteria were derived from the Mertz neck injury criteria. Para 5.2 sets Injury Assessment Reference Values (IARVs) as guidelines for assessing injury potential. These IARVs refer to a human response level below which a specified significant injury is considered unlikely to occur. However, being below the IARV does not assure that significant injury will not occur. The IARV for neck injury is a time dependant criterion however it does not quantify likelihood or extent of injury. The terms "Likely, "Unlikely, "Significant Injury" are not defined.

(c) Nij Criteria [9]. This is the neck injury criteria used by National Highway Transportation Safety Administration (NHTSA). NHTSA established critical limits in four types of neck loading determined to be dominant in automotive crashes. They were axial loading (tension & compression) and sagittal plane bending moments (flexion & extension). These criteria were developed using previous biomechanical research experiments using human volunteers, porcine subjects and (Post Mortem Human Subjects) PMHSs. The current Nij "performance limits" is set at 1.0 which represents 22% risk of greater than AIS 3 injury. This criterion has been deemed inadequate for inertial loading with head supported masses. The other major drawback is that it was developed for evaluating restraint systems in automobiles and therefore the primary force assessed was -Gx. It may have limited use in assessment of Parachute Opening Shock (POS) in aviation.

(d) Lower Neck BEAM Criterion [10]. This injury criterion was developed using PMHS which were mobile only up to T2 vertebral segment. This might have caused kinetic response to be different. Hence, BEAM Criterion is not considered to be accurately predictive when compared to Nij or NIC. However, this criterion was the first to use statistical tools like Survival Analysis to develop risk curves. This criterion too lacks data on head supported mass and hence is not applicable for evaluation of neck loads with HMDs.

(e) USN Ejection Neck Injury Criteria (NIC) [11]. The United States Naval Air Systems Command has put forth a set of neck injury criteria that is a set of metrics used to assess potential neck injuries in ejection called NIC. It incorporates 12 neck injury criteria, which includes 6 modes of neck loading evaluated at 2 locations in the neck, upper and lower. Some of these criteria have injury probability functions and some do not. It is primarily a compilation of existing criteria at that time with an algorithm to apply all of them.

(f) USAF Interim HMD Criterion (Knox Box) [12]. Perry and Buhrman studied the inertial properties of helmets and this developed into an interim criterion for acquisition process of HMDs. The criteria were applicable to the ejection profiles of two ejection seats and HMDs of two types of weights. The mass and its distribution affected the risk of neck injury during ejection. This risk function though developed for the HMDs considered only the catapult phase of ejection. Moreover, in the absence of risk injury functions did not provide any guidance towards improvements of the system to designers.

(g) Tensile Neck Injury Criterion [13]. Carter et al. developed a tensile neck injury criterion for use in the ejection environment. This criterion sought to address the problem with other neck injury criteria where frontal flexion was primary loading mechanism, as in the automotive industry for frontal crashes. This criterion was the first to generate injury risk curved based on combined human/PMHS data set. However, the use of unidirectional loading only makes the criterion incomplete.

Fundamentals of ideal neck injury criteria. A study of the numerous criteria that have been developed over the past decades to evaluate neck injury point towards certain desirable features of an ideal neck injury criteria. These have been listed below:-

(a) The criteria should have the minimum possible number of components.

(b) It should be multi-axial in nature.

(c) It should account for head supported mass.

(d) It should encompass the range of target population.

(e) It should state the risk/probability of injury.

(f) It should define the injury level/severity associated with that risk.

Multi-Axial Neck Injury Criteria (MANIC). The only criteria considering most of the above criteria is the Multi-Axial Neck Injury Criteria (MANIC). It was first conceived by Perry et al in 1997 [14]. However, the concept of the equation alone could not translate into applicable criterion without adequate aviation specific data by various workers [6,9,15]. The calculated MANIC score was further extended into usable neck injury criteria by calculation of Risk-Injury curves using Survival Analysis by Parr et al [6,9]. A detailed exposition of the concept of MANIC in different axis is given in a thesis by JC Parr [16]. Further to this, the Multi Axial Neck Injury Criteria (MANIC) Gx, Gy, and Gz calculations and limits were developed and adopted by MIL-HDBK-516 to define neck safety criteria for new and modified USAF aircraft ejection systems [17]. At about the same time, MANIC was also recommended for use by Training Aircraft Division of US Air Force Life Cycle Management Center at Wright Patterson Air Force Base for the Advanced Pilot Training (APT) Program [18].

Characteristics of MANIC. MANIC in its original form is composed of six factors. The equation for MANIC is: -

$$\text{MANIC} = \sqrt{\left(\frac{Fx}{Fxcrit}\right)^2+\left(\frac{F_y}{F_{ycrit}}\right)^2+\left(\frac{F_z}{F_{zcrit}}\right)^2+\left(\frac{Mx}{Mxcrit}\right)^2+\left(\frac{M_y}{M_{ycrit}}\right)^2+\left(\frac{M_z}{M_{zcrit}}\right)^2} \quad [14]$$

F_x = observed x direction shear loading

F_{xcrit} = critical intercept value for x direction shear loading

F_y = observed y direction shear loading

F_{ycrit} = critical intercept value for y direction shear loading

F_z = observed axial loading ($+F_z$ = tension, $-F_z$ = compression)
F_{zcrit} = critical intercept value for axial loading (different for tension/compression)
M_x = observed moment about the anatomical x axis (side bending)
M_{xcrit} = critical intercept value for side bending
M_y = observed moment about the anatomical y axis (sagittal plane anterior/posterior bending,
$+M_y$ = flexion,
$-M_y$ = extension
M_{ycrit} = critical intercept value for sagittal plane moments (different for flexion/extension)
M_z = observed moment about the anatomical z axis (neck twisting)
M_{zcrit} = critical intercept value for neck twisting

The equation considers in its numerators, three forces in three axis and three moments in three directions. The denominators give the critical load values which are based on subject weight. The weight based critical values are given in Table 1.

Table 1. Weight based critical values for Forces and Moments [17, 18]

Manikin Size	Manikin Mass	Human Mass	Component	Force		Component	Moment	
	(lbs)	(lbs)		(in)	(N)		(in lbs)	(N m)
Small Female Hybrid III (for 103-135 pound manikin)	103	<114	F_{xcrit}	405	1802	M_{xcrit}	593	67
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	872	3880	M_{zcrit}		
			$+F_{zcrit}$ (tens)	964	4287	$+M_{ycrit}$ (flex)	1372	155
	125	114-130.5	F_{xcrit}	496	2206	M_{xcrit}	845	95
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1099	4889	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1214	5400	$+M_{ycrit}$ (flex)	1939	219
	136	130.5-143	F_{xcrit}	522	2322	M_{xcrit}	912	103
Mid Male Hybrid III (for 136-199 pound manikin)			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1157	5147	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1278	5685	$+M_{ycrit}$ (flex)	2094	237
	150	143-161	F_{xcrit}	561	2495	M_{xcrit}	1016	115
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1243	5529	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1373	6107	$+M_{ycrit}$ (flex)	2333	264
	172	161-186	F_{xcrit}	625	2780	M_{xcrit}	1195	135
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1385	6160	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1530	6806	$+M_{ycrit}$ (flex)	2744	310
	200	186-210	F_{xcrit}	683	3038	M_{xcrit}	1364	154
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1513	6730	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1671	7433	$+M_{ycrit}$ (flex)	3133	354

Large Male Hybrid III (for 200 - 245 pound manikin)	220	210-232.5	F_{xcrit}	777	3456	M_{xcrit}	1584	179
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1673	7440	M_{zcrit}		
			$+F_{zcrit}$ (tens)	1847	8216	$+M_{ycrit}$ (flex)	3673	415
	245	232.5+	F_{xcrit}	836	3719	M_{xcrit}	1850	209
			F_{ycrit}			$-M_{ycrit}$ (extens)		
			$-F_{zcrit}$ (comp)	1853	8243	M_{zcrit}		
			$+F_{zcrit}$ (tens)	2047	9106	$+M_{ycrit}$ (flex)	4248	480

Mathematical Features of MANIC

The following are certain salient points that are mathematically distinctive regarding the MANIC equation: -

(a) The MANIC equation uses square root of squares. Therefore, this removes the negative numbers (direction of forces) when calculating the final score.

(b) The use of critical values converts each component into a ratio. This results in normalisation of the load magnitude across all components.

(c) The use of occupant size (bodyweight) based critical values ensures that the same criteria can be used across occupant sizes (normalisation for body size).

(d) The use of squares adds weightage to any of the normalised components that have relatively large values. This ensures that due importance is given to that component of either force or moment during the evaluation.

Applying MANIC

The numerators of MANIC are derived from experimental data such as the windblast test using anthropomorphic Hybrid III dummies. The dummies are so instrumented that upper neck data for the forces in the three axis and the moments in the three directions can be plotted. From this, the peak instantaneous loads in each of the six components is tabulated. This forms the data input for numerators in the MANIC equation. The MANIC value or score thus calculated is plotted on a graph which has Abbreviated Injury Score (AIS) 2+ [19] probability on the 'y' axis and MANIC scores on the 'x' axis. The graph is shown in Figure 2 [17,18].

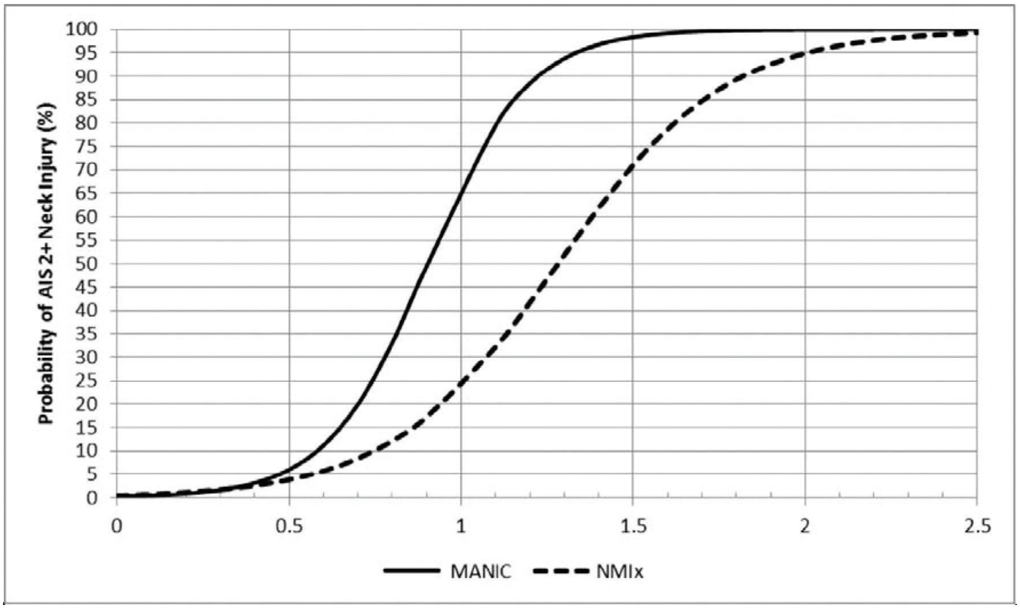

Fig 2. Abbreviated Injury Score (AIS) 2+ probability on the 'y' axis and MANIC scores on the 'x' axis [17,18]

The graph shows that a MANIC score of 0.5 means that there is a 5% probability of incurring an injury of severity AIS 2+. The USAF Aircraft System Specification for the Advanced Pilot Training (APT) Program recommends that up to 450 KEAS MANIC score of 0.56 is acceptable and above 450 KEAS a MANIC score of 0.65 is considered acceptable. Considering the nature of military flying and the chances of ejection over remote or hostile territory, approximately 5% risk of moderate (AIS 2+) injury is considered acceptable.

MANIC: Current Status

Though the concept of MANIC in the form of its initial equation was given in 1997 by Perry et al, the development of critical values for all six components has not been completed till date. The current status of development of critical loads criteria and the associated risk probability curves in each axis is given below.

(a) MANIC in Gx axis is well defined. The non-injurious data from 73 human subjects was obtained with HMDs weighing 1.8 to 2 kg at Gx acceleration levels of 6 to 8 G. Injurious forces from PMHS data has been derived from 06 cadavers at Gx levels of 32 to 39 G [15].

(b) MANIC in Gy is well defined. The non-injurious human data from 56 subjects was obtained with HMDs weighing 1.36 to 2 kg at Gy acceleration levels of 5 to 6 G. Injurious forces from PMHS data has been derived from 09 cadavers at Gy levels of 8.5 to 19 G [20].

(c) MANIC in Gz is well defined only for tensile forces. This is the kind of forces that would be observed in windblast where the force acts to distract the cervical vertebrae. Windblast testing of HMDs gives this kind of data. The non-injurious data from 208 human subjects was obtained at force levels of 34 to 149 N in the Gz axis. The injurious forces from PMHS data was obtained from 22 cadavers at force levels that caused AIS 2+ to 3+ injuries [16].

(d) MANIC in Gz axis for compressive loads lacks aviation specific experimental data till date. Therefore, the critical values for loads continue to be those used by National Highway Traffic Safety Administration (NHTSA) [21]

Recommendations

(for qualification criteria in Windblast Testing of Head mounted loads)

The legacy criteria especially AGARD AR 330 is based on automobile industry data where the primary crash force was in the Gx direction. Even though, the document contains graphs for critical cut-off values in all three axes, the experimental conditions are not representative of the aviation environment. Moreover, AGARD AR 330 and the subsequent Nij criteria which has been applied to certain ejection and windblast tests fail to provide complete information regarding the probability/risk of occurrence and severity of injury. Thus, the pass-fail criteria make value-based judgement impossible to make regarding a particular type of aircraft or situation. MANIC even in its present form bears the potential of addressing the issues of multiple axis consideration, occupant size consideration and risk severity curves for injury in the aviation environment.

Since the Gx compressive load data is not complete for MANIC, for ejection testing, AGARD AR 330 may continue to be used till such time experimental aviation relevant data is available and the probability risk curves drawn using updated critical load values.

In view of the above, MANIC in its present state should be used as qualification criteria for windblast testing of aircrew helmets.

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