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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD ADVISORY REPORT 317

The Musculoskeletal and Vestibular Effects of Long Term Repeated Exposure to Sustained High-G

(Les Effets Musculosquelettiques et Vestibulaires de l'Exposition Répétée et Prolongée aux Facteurs de Charge Elevés Soutens)

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NORTH ATLANTIC TREATY ORGANIZATION

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(Les Effets Musculosquelettiques et Vestibulaires
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This Advisory Report has been sponsored by
the Aerospace Medical Panel of AGARD.

North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

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Preface

High performance aircraft capable of sustaining 9 G have been operational in NATO countries for two decades. Future fighter aircraft may be capable of 12 G. Since World War 1, "high performance" aircraft have developed levels of G that were above human tolerance limits of consciousness. However, other acute physiologic/anatomic limitations have never been identified even though levels of G that can be sustained by aircraft have tripled. But we know less about health problems that can develop from repeated high-G exposure over the "life-time" of fighter pilots. Aircraft capable of sustaining 7 G have been operational for over three decades without evidence of any chronic health problems. Yet the 2 G increase above 7 G to 9 G is substantial and since the human body is designed to function only at sustained 1 G (Earth's gravity), some chronic physiologic/anatomic limitations can be expected as higher G levels are obtained. The spine and vestibular systems are likely candidates to be the limiting structures since they are directly loaded by increased G. Medical concerns were expressed during the AGARD Conference of 24th–28th April 1989 (AGARD-CP-471) entitled "Neck Injury in Advanced Military Aircraft Environments". AGARD/AMP Working Group 17 (WG 17) entitled "The Musculoskeletal and Vestibular Effects of Long Term Repeated Exposure to Sustained High-G" was formed in response to those medical concerns.

The membership of WG 17 was Wg Cdr D.J. Anton, Great Britain, Chairperson; Professor Dr W.J. Oosterveld The Netherlands, Vice Chairperson; Médecin en Chef J. Flageat, France; Dr A. Léger, France; and Dr R.R. Burton, United States. The first official meeting of WG 17 was May 1991 in Pensacola, Florida, United States. Subsequent WG 17 meetings were held at Farnborough, RAF/IAM, United Kingdom, September 1991; Cesme, Turkey, April 1992; and Oslo, Norway, October 1992. Ad Hoc meetings of WG 17 were held in Victoria, British Columbia, Canada, May 1993 and Lisbon, Portugal, October 1993.

The WG at the Farnborough meeting decided to write an aeromedical review (AR 317) on the WG title, but little progress was made during the regular meetings because of organizational problems. With the resignation of our chairperson late in 1992, the WG requested and was given an unofficial extension for completion of AR 317 by the end of 1993. Professor Oosterveld assumed the duties of chairperson at the Victoria ad hoc meeting of WG 17. Dr Burton, with the expert assistance of Ms Rose Reyes, agreed to supervise the final compilation, word processing, and editing of AR 317. Also at that time, expertise critical for the spine sections was incorporated into AR 317 with major contributions by Mr John Firth and Sqn Ldr Ian McKenzie of Great Britain.

Additional acknowledgements in the preparation of AR 317 include:

Major A. Bell, US
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Dr V.M. Voge-Black, US.

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Préface

Les aéronefs à hautes performances capables de soutenir 9 G sont opérationnels dans les pays de l'OTAN depuis vingt ans. Les futurs avions de combat pourraient atteindre 12 G. Depuis la première guerre mondiale, les aéronefs à "hautes performances" ont continué à autoriser des facteurs de charge bien supérieurs aux seuils de tolérance de la conscience humaine.

Cependant, aucune autre limitation physiologique ou anatomique majeure n'a jamais été identifiée, bien que les facteurs de charge supportables par les aéronefs aient triplés. Nous ignorons encore les problèmes de santé susceptibles de se déclarer suite à l'exposition répétée aux facteurs de charge élevés durant toute la carrière d'un pilote de chasse.

Des avions capables de soutenir 7 G sont opérationnels depuis trois décennies et rien n'indique qu'ils sont à l'origine de problèmes de santé chroniques. Néanmoins, l'augmentation de 2 G, de 7 G à 9 G est appréciable et puisque le corps humain n'est fait pour fonctionner qu'à 1 G soutenu (gravité de la terre), il faudrait s'attendre à des limitations physiologiques/anatomiques chroniques au fur et à mesure de la montée en G. Les systèmes vertébraux et vestibulaires sont des candidats potentiels en tant que structures limitatives, puisqu'ils reçoivent directement des charges créés par la montée en G. Des préoccupations d'ordre médical ont été exprimées en 1989 lors de la conférence AGARD sur "Les Lésions du Cou dans les Aéronefs Militaires Avancés" (à Munich du 24 au 28 avril 1989 – AGARD-CP-471). Le groupe de travail AGARD/AMP No 17 sur "les Effets Musculosquelettiques et Vestibulaires de l'Exposition Répétée et Prolongée aux Facteurs de Charge Elevés Soutenus" a été créé pour répondre à ces préoccupations.

Les membres du WG 17 furent le Wing Commander D.J. Anton, Grande Bretagne, Président; le Professeur Dr W.J. Oosterveld, Pays-Bas, Vice Président; le Médecin en Chef J. Flageat, France; le Dr A. Léger, France; et le Docteur R. R. Burton, Etats-Unis. La première réunion officielle du groupe a eu lieu en mai 1991 à Pensacola, Fl., Etats-Unis. Par la suite, le WG 17 s'est réuni à Farnborough, RAF/IAM, en Angleterre au mois de septembre 1991, à Cesme, en Turquie, au mois d'avril 1992, et à Oslo, en Norvège, au mois d'octobre 1992. Des réunions ad hoc du WG 17 ont été tenues à Victoria, B.C., Canada, au mois de mai 1993 et à Lisbonne, Portugal, au mois d'octobre 1993. Lors de la réunion de Farnborough, le groupe de travail a décidé de rédiger une étude aéromédicale sur le sujet (AR 317), mais très peu de progrès ont été enregistrés au cours des différentes réunions en raison de problèmes d'organisation. Suite à la démission du président du WG vers la fin de 1992, le groupe a demandé, et il lui a été tacitement accordé un délai supplémentaire, en prévision de l'achèvement de l'AR 317 avant la fin de l'année 1993. Le Professeur Oosterveld a assumé les responsabilités de président lors de la réunion ad hoc de Victoria. Le Dr Burton, avec le concours expert de Mme Rose Reyes, s'est chargé de la supervision, de la mise en forme, de la saisie et de l'édition de l'AR 317. Parallèlement à ces activités, des contributions expertes ont pu être intégrées aux chapitres concernant la colonne vertébrale, grâce aux prestations de Mr John Firth et de Squadron Leader Ian McKenzie de Grande Bretagne.

Nous tenons à remercier également les personnes suivantes pour l'aide qu'elles ont bien voulu fournir lors de la rédaction de l'AR 317:

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Medical concerns of mechanical loading of biological systems during repeated sustained acceleration exposure of high performance aircraft were expressed during an AGARD Conference, 24-28 April 1989 (4) entitled "Neck Injury in Advanced Military Aircraft Environments". Biological systems of primary concern were direct effects on the spine causing neurologic injury and on the otoliths of the vestibular system causing disorientation related pathologies. However, besides these direct effects, secondary vestibular effects can occur from cervical pathologies (136). The technical evaluation and overview of that conference concluded that "large gaps" exist in our clinical and biomechanical knowledge of the problems of neck injury in high performance aircraft. Further studies on the epidemiology of acute and chronic neck injury resulting from in-flight G were recommended (13, 14).

This Advisory Report (AR) also addresses those concerns with a definition of the physical dimensions of the environment produced by operational high performance aircraft relating those to the potential medical effects of that environment on those biological systems of interest, a review of the relevant literature, an identification of the biological risks, and recommendations of a specific course of action as required to alleviate those concerns identified in this AR.

1.2 THE PHYSICAL ENVIRONMENT OF AERIAL COMBAT MANEUVERS:

Since 1973, high performance aircraft (i.e., F-15) capable of sustained accelerations that produce inertial forces routinely of +9 Gz[1] have been operational in the United States Air Force (USAF). Since that time, many NATO nations and the United States Navy have put into operations these high G aircraft (i.e., F-15, F-16, F-18) as have the Former Soviet Union (e.g. MIG-29). This G capability is an increase of 2G over previous high performance aircraft such as the F-4 that had been in the USAF inventory for 15 years. Understandably, the medical history of F-4 like pilots may not be strictly relevant to aircrew of these 9G aircraft.

High performance aircraft are designed by definition to be highly maneuverable creating an aerial combat maneuver (ACM) environment that has both high and low G with rapid changes in these different G levels. In addition, there is occasionally some -Gz component in the ACM. Although every ACM is different, depending on the type of aircraft, skill of the pilot, and those of the adversary, the ACM environment has been described previously by Gillingham et al (66). Mean and maximum values are summarized in Table 1. These ACM descriptions identify the physical loading on the body as well as the rate of change of these loads.

1) Unless otherwise noted, all references to G are inertial forces directed footward along the body's longitudinal axis; i.e., produced by positive headward accelerations.

TABLE 1-I: MEAN AND MAXIMUM VALUES FOR AERIAL COMBAT MANEUVERS FOR VARIOUS AIRCRAFT FOR SPECIFIED NUMBERS OF ENGAGEMENTS (66)

Aircraft		Max,G-onset Rate (G/s)	Peak G Load (G)	Time spent at or above: 5G (s)	6G (s)	7G (s)	8G (s)	Engage. Duration (s)	Fraction of Engage. Spent at or above: 5G	6G	7G	8G	# of Peaks at or above 5G	6G	7G	8G
F-4E (7 engagements)	Mean	1.13	6.0	13.1	1.2	0	0	176	.07	0	0	0	2.9	0.7	0	0
	Max	1.8	6.8	29.9	3.5	0	0	332	.12	.01	0	0	5	2	0	0
F-5G (12 engagements)	Mean	1.13	5.9	9.5	1.4	0.4	0	66	.15	.02	0	0	2	0.8	0.2	0.1
	Max	3.0	8.2	25.0	10.5	4.4	0.5	158	.37	.20	.08	.01	10	6	1	1
F-15G (58 engagements)	Mean	2.06	6.83	21.8	8.4	1.3	0	143	.17	.07	.01	0	3.7	2.1	0.6	0.1
	Max	6.3	8.2	72.2	45.5	18.1	0.8	303	.60	.30	.10	0	14	9	6	1
F-16G (21 engagements)	Mean	1.73	7.11	20.3	7.8	2.0	0.2	160	.14	.06	.02	0	3.1	1.7	0.8	0.14
	Max	3.0	8.4	56.4	33.1	10.2	1.9	292	.51	.29	.16	.02	11	3	3	1

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In summary then the ACM has peak loads of 9G that can recur frequently, with varying G for several minutes, multiple G onset per second, with an average integrated time x G of 1000 G sec for a 3 minute ACM. This ACM can be repeated several times every day, several days per week per month per year. Over the "life time" of a fighter pilot whose career flying high performance aircraft may span 20 years, it is possible that they will each be exposed to 18,720,000 G x sec that represents a total period of time of 36 days exposed to an average of 6G -- a G level that requires the use of an AGSM.

1.3 PHYSICAL EFFECTS OF G LOADING:

The ACM environment provides sustained increased G that spans periods of time of sufficient length that size and scale effects are a consideration in helping define the hazards of G loading on these biological systems. These effects as they relate to chronic acceleration were first described by Smith (179). Relating scale factors to physical properties of systems (in our case, biological systems) is the basis for the "principle of similitude". Similitude as it relates to strength and loading is particularly important considering the effects of increased G (loading) on the strength of the spine over sustained periods of time.

In nature, the skeleton responds to increased loads (body mass) in larger animals with a relative increase in the amounts of bony structure. This greater than expected increase in skeletal mass as body mass increases is found in animals as they increase their size; e.g., mouse has a skeleton that is 8% of its body mass, whereas dogs have 14% and the human about 18%. This skeletal mass relationships for all animals can be expressed mathematically with the following equation:

$$S_m = aM^{1.175}$$

Where

S_m = skeletal mass

M = body mass

a = (inter-intra) species constant

The larger skeletal mass is necessary to prevent spontaneous fractures from the weight of the body at earth's gravity since the load increases in proportion to the cube and the load-bearing structures increase only in proportion to their cross-sectional area; i.e., proportion to its square. The amount of the load on the supporting structure is defined as the specific load (kg/cm^2) which is equal to 1.28 x scale. Specifically, the specific load increases during exposures to 9G from 1.28 to 11.52; i.e., the weight increases 9 times with no increase in the load-bearing structure. In order to properly support that much weight, a pilot would require the skeletal mass of a 910 kg animal; e.g., a horse. In addition, the human's posture is upright, loading the spine in an "unnatural" manner; i.e., it was designed to support quadripedal posture and motion.

The ligaments of the spine are considered able to support accelerations of up to 40G for the appropriate posture and acceleration. The anatomical situation of the spine reflects a model where a head with a weight of 4900 grams balances on top of 7 cervical fragile vertebrae separated by thin viscoelastic intravertebrae discs. The balance is kept by 44 cervical area muscles. These seven cervical vertebrae are connected to each other by a system with 38 joints which permits maneuverability and mobility in all three planes. Therefore the spine can be considered an extremely capable structure, but that can be at risk with high loads.

However even with high loads on the spine of the human during high G exposures, incidences of spinal fractures or spinal disc ruptures in either pilots or healthy centrifuge subjects are rare considering millions of high G exposures (8, 169). These cases of vertebrae fracture and disc rupture occurred with twisted head positions or during unexpected (unprepared) G onset. Compression stress alone apparently is not capable of rupturing vertebral discs (140). On the other hand, such high specific loads that are repeated on a regular basis over many years may well "fatigue" the supporting structure so that potentially spinal diseases can eventually occur. This AR will attempt to ferret out that potentially important situation.

The rate of change of these loads can be considered relevant to the hazard since rapid G changes provide less time for biological functional changes in preparation of these loads. This rate change of G probably effects supporting muscles, tendons, and ligaments the most, since they best prepare for the increased load. However, loads with rapid G onset are primarily supported by the spinal column with the viscoelastic properties of the vertebrae disc. If repeated exposures only

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slightly traumatize the disc, but with disc degeneration that causes less disc elasticity (as occurs with age), then disc rupture could be a response to not only the G load, but also the rapid rate of G onset.

Shear also may adversely effect the spinal cord since its specific weight is considerably less than the covering bone of the spinal vertebrae. Although the cerebral spinal fluid does a superb job protecting this nervous tissue, significant impacting forces such as a heavy blow to the head can cause brain damage. One instance of brain injury has been reported with high $+G_z$ exposure (approximately 9G) that resulted in temporary ataxia, dyssynergia, past pointing dysarthria, and dysgraphia. He fully recovered in 6 months (147). Therefore, the potential exists for the bony spine with its high specific weight positioned longitudinally in the $+G_z$ environment to move differentially in relation to the spinal cord suspended in the cerebospinal fluid injuring it and the spinal nerve roots. Its probability of occurrence will be examined in this AR as will recommendations to conduct studies if considered necessary.

Possibly, rate of change of G also plays a significant role in the physical shear phenomenon involving the otoliths since the inertia of otoconia of this structure with its high specific density accelerate more rapidly than the end organs in response to the same G. Therefore, the structure of the vestibular system would appear to be at considerable risk during high G onset exposure. Such damage may occur but because of the compensatory ability of the vestibular system, functional problems from these significant injuries may be only transitory and therefore difficult to measure.

1.4 G PROTECTION:

Protection by definition is "to cover or shield from exposure, injury, or destruction" (199). G-protection does not nor will it ever protect since G is pervasive (as is gravity). Quite to the contrary, G-protection increases the G level that the human can tolerate thereby increasing the G-exposure hazard. G-protection systems are directed towards supporting only the cardiovascular, since that physiologic function limits human tolerance for aircrew. These G-protection systems are not designed with the spine or the vestibular system in mind; i.e., at 9 G these systems are directly exposed to 9 times the force of gravity.

Aircraft designers suggest that 12 G maneuvering is very possible in near-term fighter aircraft. Aircrew protection against such high levels of G argue for reducing the eye-heart vertical distance by reducing the seat-back angle; i.e., aircrew will be unable to tolerate 12 G without significantly pronating or supinating pilots. However, it must be remembered that aircraft maneuverability was increased from 7 G to 9 G without concern for protecting pilots at higher G levels. Sustaining 9 G was revolutionary indeed requiring its own descriptive nomenclature "High Sustained G (HSG)". Only now are 9 G protection systems becoming operational -- some 20 years after the introduction of 9 G aircraft. These G protection systems (that do not utilize reclining technologies) will allow many aircrew to "tolerate" 12 G. It is reasonable then to suggest that perhaps aircrew of future 12 G aircraft will fly upright using 9 G protection systems and increasing even more the specific load on the vertebrae of the spine and the vestibular system. However even reclined, the spine and vestibular systems are subjected to all of the G that the aircraft develops.

At some point, the G load will directly cause medical problems. These problems will probably develop in physiology functions that are directly effected by the G and not "protected" by G protection; i.e., the spine and vestibular system. It is appropriate, therefore, to examine in some detail the potential for medical disorders associated with repeated exposures to HSG.

1.5 REVIEW OF ACCELERATION LITERATURE:

This AR will review, in considerable depth and critique, published research studies that directly and indirectly impact this topic of spine and vestibular injury. The following review considered only briefly those publications that directly involve HSG as well as mention the corollary environment of the parachutist.

1.5.1 Spine:

Since the cervical portion of the spine has by far the greatest range of motion and since fighter pilots are always concerned about who is behind them ("check six"), the neck is expected to take the most abuse during high G maneuvers (109). This assumption appears to be valid since several surveys have shown neck injury to be prevalent in fighter pilots, particularly those flying the higher performance aircraft (8, 21, 77, 109, 169, 191, 192, 211). The vast majority of fighter pilots reported some form of acute neck injury related to ACM in high performance aircraft. Injuries were highest in those pilots that flew

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aircraft with the highest G capabilities; e.g., F-16, F-18, and F-15. Some injuries were severe enough to lose flying time. About 50% of the injuries were severe enough to reduce pilot performance (109). Neck injuries appeared to occur more frequently in the older pilots, particular involving major injuries (191, 192). Although these injuries usually involved the soft tissue of the neck (i.e., ligaments, tendons, muscles, etc.), some speculation exists that some of this pain may be originating from nerve endings in the cervical intervertebral disc (76).

Although acute neck injury does not necessarily indicate the existence of degenerative types of spinal diseases, chronic neck pain resulting from repeated high G exposures has been reported (189). Certainly, the increased incidence of acute neck injury in the higher performance aircraft suggests that the risk to cervical spinal injury is increased. Inasmuch as our understanding of the severity of neck injury from high sustained G (HSG) is limited, pilots are warned to take preventive measures: 1) increase neck muscular strength with exercise, 2) neck muscle "warm-up" before pulling G, 3) return to high G ACMs gradually especially after not flying for a few days, and 4) minimize neck/head movement during high G exposure (192).

Spinal degenerative diseases that effect the cervical vertebrae and discs such as progressive cervical osteoarthritis, vertebral fracture, and cervical disc degeneration have been surveyed (retrospective studies) in pilots of high performance aircraft with varying results (65, 80, 126). McNish (126) reported no significant increase in cervical diseases in pilots of fighter, attack, and reconnaissance (FAR) type aircraft compared with tanker, transport, and bomber pilots. However, two other surveys found significant cervical pathologies associated with HSG exposures in fighter pilots. Hamalainen, et al, (80) using magnetic resonance imaging (MRI) compared senior fighter pilots with sex and aged matched non-G exposed controls. He found a significant increased incidence in the fighter pilot population, particularly comparing the more severe type of disc degenerative changes principally in the C3-4 disc. Gillen and Raymond (65) found increased significant deterioration resulting in cervical osteoarthritis and disc space narrowing (using x-ray) in young fighter pilots compared with controls. But their lesions were located in the C4-5 and C5-6 vertebrae spaces. The C5-6 disc location is most commonly related to age-related cervical disc degeneration (13, 76).

These three small population surveys unfortunately complete the extent of our knowledge of musculo-skeletal effects of long term repeated exposure of pilots to HSG. Although suggestive that repeated HSG is related to cervical spinal degenerative disease, these surveys do not constitute the definitive research necessary to demonstrate causal relationships.

Spinal discs of 22 male centrifuge research subjects who had been exposed to HSG on numerous occasions were examined using MRI. Although the incidence of spinal disc abnormalities was extremely high in these young subjects (21-33 yrs of age), it was not significantly different from 19 age-matched non-centrifuged controls (29). Interestingly, not all spinal pathology related to HSG is located in the cervical area. Shaw (178) reported on two case studies that involve acutely herniated discs in the lumbar region in pilots exposed to HSG.

It is appropriate to also briefly consider at this time the G environment of the parachutist when high short-duration exposures have been shown to have a causal relationship to spinal injury and related chronic disease. Particularly relevant are the pathologies associated with chronic pain syndromes. It is generally accepted from sport pathology that such lesions can affect various joints, inducing chronical pain syndrome after cessation of sport activities. Apparently, no particular attention has been paid to the spine in regard of these problems, particularly at the cervical level. However, in the sixties and early seventies, some studies have addressed the problem of chronic diseases affecting the spine of paratroopers. In France, Teyssandier (187) has described the "parachutists' spine syndrome" which is essentially a pain syndrome localized at a precise level, usually not easily related to a remembered trauma. The nature of this syndrome seems quite similar to the "loading syndrome" of the spine described elsewhere (72, 189). Interestingly enough, x-ray investigations conducted on paratroopers presenting such chronic pain syndrome showed no radiological signs in almost 50% of the cases. Unfortunately, these studies were made without real control groups, though considerably reducing their value. Whether such syndromes, pain without radiological signs, could result at the cervical level from repeated exposure to HSG is an open question. New techniques allowing soft tissues and ligament investigations could be used to monitor this kind of problem. This question is addressed later in this report.

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1.5.2 Vestibular System:

Research on the effects of HSG and the ACM on the vestibular system of animals and humans has been minimal even though the otolith organs of the vestibular system respond to linear accelerations and therefore considered to be at risk during HSG exposures. Unfortunately, most of the recommendations of this AR regarding the vestibular system will be based on anecdotal evidence or speculation.

The affects of high acceleration on vestibulo-ocular responses of humans were examined by Dowd (52) in 1967 using centrifugation. Unfortunately, coriolis induced effects tend to confound research on the vestibular system using the centrifuge because of its circular motion, especially with the short radius of most human-use centrifuges (usually about 6 meters). However, the ACM also develops coriolis forces, although reduced significantly from those of centrifugation.

The Dowd study showed definite modifications in vestibular responses post-centrifugation. He speculated that the otoliths were primarily affected perhaps a function of missing otoconia or loosened fragments of otolithic membranes. This hypothesis is supported by Parker et al (143) using guinea pigs exposed to 12G for 195 sec to 100G for 20 sec. They reported moderate to severe loss of otoconia from the maculae of both the utricules and the saccules, and a distortion of the cupula or a crista. They concluded that the more common transient disorientation reported by many centrifuge subjects may be related to stimulation or injury of the otolithic membrane to a lesser degree.

1.6 SUMMARY:

Since information on spinal and vestibular injury as related to exposure to HSG is limited, additional information on injuries inflicted by similar forces but produced by other environments will be reviewed in later sections of this AR. From the information presented in this introduction, it is clear the ACM environment develops inertial forces that load the spinal column to a level that appears to reach or exceed the static limits of that biological system. A brief review of the literature provides evidence that some significant acute and perhaps more chronic degenerative types of injuries may be related to HSG exposures that occur during ACM in pilots of high performance aircraft. Less information is available for the vestibular system as it relates to this environment.

Over the years, nagging concerns about the medical hazards of such high levels as 9G -- 9 times above the force of gravity to which our body is physically and physiologically adapted -- are occasionally raised, but without any substantiation with fact. The spine and otolithic organ appear to be among the most potentially vulnerable to the hazards of this biodynamic environment if, of course, HSG is hazardous. These imponderables will be considered by this AR with recommended courses of action.

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CHAPTER 2

THE ANATOMY AND BIOMECHANICS OF THE SPINE

2.1 INTRODUCTION

The challenge posed to seated humans by high performance aircraft (HPA) operations at <+15Gz has to be considered in spinal and central nervous systems not designed for and poorly adapted to erect posture (110, 163). In evolutionary terms, high-Gz is being used by a cohort already aged and beyond the natural life expectancy our spines have been engineered to support. Indeed, intervertebral disc degeneration is manifest even in teenagers (23, 24, 128, 177, 186, 209). Meanwhile in the general population exposed only to +1Gz, present postural habits ensure components of the spine are at their failure boundaries in many individuals for much of the time (35, 71, 82, 99, 175). Not surprisingly, spinal morbidity is the primary cause of loss of working time in the adult, physically active populations of most NATO countries (68, 133, 165). The reader is referred to Chapter 3 for more information on occupationally related special injury.

2.2 COMPARATIVE ANATOMY OF THE SPINE

In evolutionary terms, before our ancestors assumed the erect posture, the function of the spine was to act as a horizontal mobile but intrinsically stable axial structure under -Gx. This dichotomy of design objectives was satisfied by arranging it as three transversely segmented columns in suspension. The principal components maintaining its configuration remain the continuous anterior longitudinal ligament [ALL] and the posterior facet joints between each segment. Each segment comprises an anterior vertebral body and posterior pars interarticulares, supporting the facet joints on either side and themselves joined over the spinal canal by the laminae. Posterior from the junction of the two halves of the lamina in the midline extends the bony spinous process. Transverse processes extend out laterally, one on each side, from the junction of each pars and the pedicles which join the pars on each side to the vertebral body in front. Normal quadrapedal posture caused the structure to bow forward into lordosis between supporting limbs at either end, in the manner of a suspension bridge. In this configuration with the ALL in distraction [tension] and the facet joints apposed in compression, the structure is mobile but stable. If it is straightened [as by axial extension] or posteriorly bowed into kyphosis, it becomes unstable as the facet joints disengage.

Anteriorly, bridging the space between the vertebral bodies, vestiges of the notochord persist in the intervertebral discs. In the dynamic situation, they act under distraction [that is under tension rather than compression] as shock absorbers protecting the ALL from high transient axial loads and transfering such transients to the vertebral bodies, themselves arranged [unlike other long bones optimised to bear weight in compression] with widely-separated vertical peripheral cortical surfaces and light-weight vertically orientated but tension resistant cancellous centres.

This cancellous pattern is altered in the pedicles which are optimised to bear transverse [postero-anterior] tension as they hold together the anterior axially distracted and posterior axially compressed components or "columns' in Holdsworth's terminology (93). In dynamic and structural terms, the nodal focusing of transverse stresses into the pedicles and their expansion into the vertebral bodies and the interposed posterior disc, posterior disc annuli and the weak posterior longitudinal ligament comprises an intermediate, "middle" column between the distracted anterior and the compressed posterior columns. This middle column is furnished with additional lateral intervertebral neuro-central joints in the cervical spine.

With little development and less re-configuration, this horizontally arranged suspension system has been required to accept vertical +Gz loading with the assumption of the upright, erect posture (110). The transition was assisted by an intermediate arboreal phase when upper limb suspension and therefore continued axial distraction was the rule (208). We are now left with an axial skeleton designed for horizontal, ponograde activity with passive maintained stability dependent on that configuration under -Gx, yet now operated upright under +Gz, often with lordosis reduced and therefore in dynamic instability or worse, in gross anterior column compression, if lordosis is abolished and kyphosis adopted.

That this potentially disasterous arrangement did not prevent our species progression from the forests out on to the plains of the world was due to three factors.

1) The intervertebral disc proved in erect practice to be able to carry compression loads in the majority of the population for >16 years.

2) Reproduction occurred to ensure the next generation by this age.

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3) Sufficient disc degenerate "elders [>16 years of age]" survived with usable spines in a social organization able to protect the next generation to puberty.

Subsequently, the necessity of education for the further progression of human society and the associated phenomenon of adolescence while procreation is delayed now means that few under 16 years old, non-disc degenerate pilots can be trained, deployed and usefully employed before time and the reality of the human condition catches up with them.

Despite this design:function mis-match which has to be ascribed to the First Saturday of Creation as described in Genesis (62) with respect, the "Mark II" improved female model based on the early cloning works of the Second Tuesday as described in Genesis (63) exhibits only superficial improvements. Some spinal remodelling useful to erect posture had taken place before the ponograde position was abandoned and our ancestors took to the trees to survive (and to be able to be our ancesters):

1) Lung ventilation by negative phase respiration required a rib cage which doubles as an outrigged, cantilevered trapeze for the thoracic spine. This in its turn can be splinted by positive pressure breathing, PPB or the Valsalva maneuver (12).

2) The need for thoracic kyphosis to maintain overall axial neutrality introduced anterior column compression which was off-set by reducing the axial, now vertical dimension of the anterior thoracic column by anterior thoracic vertebral body "wedging" (163).

3) In the sacrum marked compensatory kyphosis is not only reflected by anterior wedging, but also by massive lateral buttressing by the fused sacral alae.

Later, a potentially disastrous major spinal structural compromise at the cranio-cervical junction -- which required 90° anterior angulation to maintain forward horizontal vision as the general spine axis rotated upwards to assume the erect posture -- was off-set by other developments. Forty-five degrees (45°) was provided immediately above the (antero-lateral) occipito-vertebral (atlanto-occipital) joints, to maintain axial balance during the development of the cerebellum. The remaining 45°, beyond the termination of the vertebral bodies at the top of the clivus, was imposed by the need to accommodate the massive development of the cerebral hemispheres.

In erect, +Gz terms, this means that rather than having to support an outrigged ever more massive head at the far end of a horizontally extended neck, a problem further compounded by the C1-2 mobility/stability compromise (54, 91, 198), the head (head and helmet) can, by appropriate design and training, be balanced at the cranio-cervical junction by the cervical paraspinal muscles to well beyond our +15Gz objectives (86). This is more comfortable than the convention in hang-gliding, more convenient than is necessary in prone position pilotage, (PPP) (11, 16, 39, 87, 111, 182, 196, 207, 214) and much less troublesome than the helmet-horse stabilization which the XVth century armorers found necessary for total, three-axis spinal protection.

This advantage is obviated by present headbox and helmet designs which ignore evolutionary development, force present HPA aircrew into cervical kyphosis and ensure they operate at maximum cervical and cranio-cervical, mechanical and dynamic disadvantage, discomfort and risk. Not surprisingly, this anatomical anarchy is rewarded by much neck pain (6, 8, 10, 13, 14, 21, 65, 76, 109), some injury (168, 169, 191, 192, 211) and unusual variations on the normal present day pattern of adult spinal degeneration (80) associated with the +1Gz cervical kyphosis ("slouching") which is the current, fashionable, unphysiological norm. The latter causes as much trouble in controls (29) and other military personnel (47, 125, 126) as well as being eventually near-universal in the general population at large (31, 61, 114, 133, 148, 164, 215). Surprisingly, only MiG-21 pilots appear immune to this otherwise universal trend (124, 185). Stupakov et al, (185) used an interesting indirect method to determine the relationship between clinical recovery time and vertebral column destruction. Their technique involved the use of acoustic emission signals from the stressed vertebral column similar to the methods used by engineers to test other stressed structures.

The lumbar and cervical spine are passively unstable unless in full lordosis. Like tall-masted sailing ships, they depend for configuration, strength and stability on their continuous dynamic "active" rigging by the "crew" of the spine, the muscles acting through their ligaments and attachments to the bony components of the spine, under constant "orders" through and from the peripheral and central nervous systems. Again like a tall ship, the spine can only be operated satisfactorily within its design constraints. Craft and crew require constant training, stressing (106) and practice to function safely, particularly in unusual circumstances, such as intended axial loading to +15Gz.

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2.2.1. Two Elements Remain to be Introduced:

1) The inter-laminar ligamenta flava and the inter- and supraspinous ligaments damp and to a degree progressively restrict spinal movement as the "neutral zone" of each joint is left and full joint range and spinal deflection approached (138, 139). In compression, they provide a progressive end-point to cervical lordosis whilst "concertina-ing" of the ligamentum flavum can compound spinal stenosis.

2) Lastly, both the ligaments and the back as a whole have a powerful sensory afferent function. "Strapping on" one's aerobatic aircraft is no idle turn of phrase, but an indication that to be "at one" with the aircraft, at least one major part of one's anatomy has to have a constant and unvarying relationship with it. "Pelvic welding" to the seat pan by the two lap straps and the G-strap is preferred. Too tight shoulder restraint restricts head and neck movement and may induce a distracting euphoria at high -Gz. Careful seat design and individual fit allowing the active maintenance of cervical and lumbar lordosis are essential to accurate and undistracted high +/-Gz pilotage.

In this fearsome situation, there are features which can be turned with advantage to the present purpose:

a) The human's aging characteristics (128, 177, 186) mean the intervertebral discs cannot be relied upon to accept anterior spinal axial compression loading over the age of 16. For practical purposes, all aircrew are "spinal degenerates". Fortunately, by recognizing the anatomical realities of the situation and maintaining cervical and lumbar lordosis. The strength and stability of the two spinal segments most at risk do not have to rely on disc compression. At the same time by maintaining physiologic disc distraction, the degenerate intervertebral disc is still able to function usefully, as disigned, as a dynamic shock absorber.

b) Whereas even in the fit youngster (<16 years) in erect passive kyphosis lumbar and cervical spines are at their static anterior compression failure boundaries, used intelligently as designed in lumbar and cervical lordosis the spine becomes a spring-like "active" system in which axial strength is not limited by anterior compression failure but rather by the spine's very much greater active whole-system performance. Rather than being the weakest (in compression) component of the +Gz loaded spine, in cervical and lumbar lordosis, the "compression-weak" anterior column contributes its great [designed for distraction] tensile strength. In distraction, the anterior column only fails in gross extension spinal injury, where peak anterior distraction levels greatly exceed those provided by +15Gz and indeed the 50G identified by STAPP (183, 184).

For maximal +Gz spinal loading performance, the keys are: cervical and lumbar lordoses with head balance on the occipital condyles. This is the mandatory high +Gz resting or "neutral" position. All movements should be made from this position, especially under increased +Gz, retaining lordoses and head balance as long as it is possible (78). Seat, cockpit and helmet design, crew selection, training and aircraft operation need to recognize and exploit these realities if both maximum operational effectiveness and minimum aircrew morbidity are to be achieved.

2.3 SPINAL BIOMECHANICS AND NEURO-ORTHOPAEDIC PRACTICE

2.3.1 Introduction

This is now a vast subject with an ever larger literature. Despite this, most of the published work is of surprisingly little value to AR317 as it dwells on the limitations of the spine's materials and component parts and demonstrates little real progress since Stapp's research (184). With exceptions (20, 28, 35, 45, 53, 68, 71, 78, 81, 134, 141, 145, 171), little effort has been made to establish how the spinal system's peculiarities can be exploited in the individual as well as the general population's best interest. Much of the present literature and opinion is reflected in relatively recent reviews (120, 130, 138, 139, 149, 180, 202).

The principle restriction of the materials work is that components are considered in isolation and often tested and reported inappropriately (99, 199, 213). The prime example is the consideration of disc compression failure as the hallmark of spinal compression performance. Even Majendie in 1816 (71) did better, but by misapplying Euler's compression theory (59) and ignoring the equal importance of distraction, Hooke's law (94) and tension in curved structures, he blighted the consideration of the spine as an active, continuously-trimmed structure with cross-bracing as well as curves, in which rapid and progressive extra-spinal as well as paraspinal muscle recruitment is available with steadily increasing leverage, particularly if lumbar and cervical lordoses are maintained.

Clinical experience supports comparative anatomy in emphasizing the importance of considering,

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preparing, training, practicing and operating the spine as a whole, as an active biological system, not limited by the sum of the post-mortem characteristics of a few of its component parts (106).

2.3.2 Biomechanics of Acute Spine Injury

Spinal injuries are occurring despite the neck having sufficient strength to carry the loads that would be anticipated on exposure to high Gz. The mechanism by which neck injury is occurring in fighter pilots is more complicated than simple compressive loads acting on the cervical spine. Extensive biomechanical investigation into the mechanism by which the musculoskeletal elements of the spine fail has been motivated by the large numbers of back injuries seen in industry and the serious consequences of traumatic injuries to the spine. Many attempts, as reviewed in Panjabi and White (140), have been made to produce disc prolapses in cadaveric spines by compressive loading. The vertebral end plate always fails before disc prolapse, even in spines with significant degenerative disease. The intervertebral disc can be torn by torsional loading beyond the physiological limit, but prolapse did not occur in these experiments. Flexion tears the posterior ligaments or fractures the posterior laminae but does not rupture the disc. Recent experiments (2, 140) have successfully prolapsed discs by applying a compressive load to a specimen that was already laterally bent and hyperflexed. This mechanism was not successful in all specimens. The specimens that did prolapse had prior disc degeneration, came from the 40-49 year age group, and from the lower lumbar levels L4-5 and L5-S1. Combinations of intervertebral joint movement that produce stress concentrations and distort the disc are needed to produce disc prolapse, rather than purely compressive forces.

In the studies cited above, preexisting disc degeneration was needed before prolapse could be produced. The mechanism by which disc degeneration occurs remains a subject of speculation. There is some experimental evidence that intervertebral discs may fail through "fatigue". Cyclic loads in both compression and torsion have been applied at rates up to 40 times per minute (132, 202). Many of the post-mortem specimens used in fatigue testing develop posterolateral radial fissures. Nixon (132) suggests when these fissures become confluent, they may provide a path through which nuclear material can escape. The avascular disc tissue has only limited capacity to repair itself. It takes 500 days to turnover the proteoglycans in dog intervertebral discs (190), thus the rate of injury could easily exceed the recuperative abilities of the disc. Disorders of the musculoskeletal elements of the spine are increasingly being considered as "cumulative trauma disorders" when occupational stresses are analyzed, in concert with the above work on "fatigue failure" (73, 96). Cumulative trauma disorders can be defined as "... disorders of the body that are caused, precipitated, or aggravated by repeated trauma...(;) the soft tissues, the back and the upper extremities are among the most commonly afflicted area " (15). Unfortunately, the literature specifically supporting this concept is limited. The mechanical properties of the disc change with age. The water content decreases from 90 percent to less than 70 percent as age increases from below 30 years to 70 years. The structure of the disc changes with collagen slowly replacing the nucleus. It is difficult to distinguish the process of aging from pathophysiologic changes in the spine (42).

Further understanding of the biomechanics of the spine is provided by mathematical modeling. The bones and ligaments of the spine, when removed from a cadaver and stripped of all of their supporting muscles, can only carry a load of about 20 Newtons (N) (117). They buckle in response to such small loads. Clearly, the muscles play an important role in maintaining the load carrying capacity of the spinal column. Gracovetsky and Farfan (68) emphasize the dynamic nature of normal spine function. Their hypothesis requires a control loop to minimize the stress in all of the intervertebral joints by adjusting the tensions of individual muscles attached to the spine. Their model implies this occurs when the intervertebral disc carries almost pure compressive loads. They suggest a number of mechanisms might injure the intervertebral disc. Lateral bending is coupled to axial torsion in the spine. Their model suggests the level of torque transmitted through the spine dynamically exceeds the static strength of the joint. If the control system fails to maintain the torque strength of the spine, a torsional overload in the spine may result. One situation in which the muscles may fail to control the stress distribution in the spine is the "misstep". This occurs during a step when a person steps down without realizing. The control system is unprepared for the sudden step down and cannot adjust the muscle tensions quickly enough to counter the impact forces of the step. Gracovetsky and Farfan's model implies injuries to the spine occur as a result of failures in the control system. More recently Panjabi (138, 139) has suggested the spinal stabilizing system should be considered as three subsystems consisting of a passive system (the bony and ligamentous system), the active

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system (muscles and tendons attached to the spinal column) and the neural subsystem. This author also emphasizes the dynamic nature of the biomechanics of the spine and also considers the possibility of injury to the spine resulting from failure of the control loop.

Pilots ejecting from military aircraft can experience spinal loads close to human tolerance limits. Several mathematical models have been developed to help understand the forces transmitted through pilots' spines on ejection, especially the cervical spine. The insights offered by these models may also apply to the problems encountered by pilots moving their heads while exposed to high Gz forces in maneuvering aircraft. Helleur et al (86) estimated the cervical spine should be able to tolerate loads seen at G levels up to 40 G with the head in an optimal position. Their model only considered head and neck motion in the sagittal plane. They found that when the force vector was applied in a non-optimal direction or the head was not optimally positioned, the tolerance level dropped steeply. Gracovetsky and Farfan (68) suggest a mechanism for cervical spine injury at G levels lower than the theoretical maximum cervical spine load. In their model, they noted at maximum voluntary effort, the muscles, ligaments and bones are only stressed to two-thirds of their ultimate strength. They interpret this to mean the organism senses impending injury and shuts down by refusing or aborting the task. In an ejection, if a pilot aborts by reflex the task of holding his head up, his muscles will relax at the worst possible moment, causing injury. They also found the seat restraint system prevented the musculoskeletal system from adopting a posture minimizing the stress distribution through the spine.

Recently, models of the spine specifically under high Gz, rather than during ejection have been developed. Snyders and Roosch (181) were able to estimate the tensions in the muscles attached to the cervical spine and the forces transmitted through the intervertebral joints. In-flight measurements of head position and G in an F-16 were input into the model. They found the helmet increased forces in the neck by a factor of 1.3 to 1.5. When the head was rotated into an extreme position, the load in the atlanto-occipital joint increased 14 times, while the load in the lower cervical spine increased 21 times. At 7 G, a highly rotated head position with moderate lateral flexion and forward flexion requires muscle tensions that are sustainable for only 10 to 30 seconds, when compared with known neck muscle capacities. The build-up of high velocities of the head relative to the torso has been suggested to cause in-flight neck injury by Raddin et al (154). They give an example of someone falling asleep in a sitting position. As the head falls forward, allowing for a drop height of 3 inches, the head can build up a velocity of 4 ft/sec relative to the torso. If the neck muscles are required to decelerate the head over a distance of 1 inch, the head would experience a 3 G deceleration. This force can produce mild neck strains. If the same calculations are applied to a freely falling head at 8 G, the neck muscles are required to produce a 27 G head deceleration, which the authors of this paper consider would produce injury. Loss of control of the head under G is a fundamental part of this hypothesis for G induced neck injury.

Despite the different approaches used by various groups modeling the head and neck exposed to high Gz, a number of common elements are apparent.

1) The first of these is head position. A high proportion of pilots experience neck injury when their heads are in an extreme position. The "check six" head movement has the highest injury potential. The Snyders and Roosch model (181) demonstrates the high muscle tensions and joint forces seen in this type of head position, while the model of Helleur et al (86) suggests the load carrying capacity of the cervical spine is sharply reduced as the head moves from a neutral position.

2) The second circumstance commonly reported as leading to neck injury is sudden unexpected application of high Gz, catching one member of a multiple crew unaware. The sudden application of force to the head could be too rapid for neural control to follow, leading to non-optimum muscle tensions and spinal positioning for the applied forces, in a manner consistent with Gracovetsky and Farfans' model (68). The mechanism suggested by Raddin et al (154) is essentially the same. The occurrence of acute injury can be explained by combinations of the above mechanisms.

2.3.3 Biomechanics of Spinal Degeneration

The question this working group set out to address is not so clear. There is very little clinical and biomechanical evidence for chronic injury to the musculoskeletal elements of the spine from high Gz exposure. Understanding this effect of high Gz on the spine is hampered by a general lack of understanding of spinal degeneration in the 1 G environment. Nonetheless, a consensus is developing in the occupational medicine arena that may be useful in the high G environment. The structural components of the spine deteriorate with age.

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This deterioration can be accelerated. Mechanisms such as those proposed by Gracovetsky and Farfan (68) and Panjabi (138, 139), injure the components of the spine, especially the disc. The injuries may be asymptomatic, as the system has a functional reserve that can compensate for individual parts that are not able to function at full capacity. The remaining fully functional parts of that system, in carrying the loads of injured components, are required to work at loads closer to their limits, making them more vulnerable to further injury. Eventually, sufficient damage accumulates to become symptomatic and the individual becomes aware of the end result of a long process of cumulative trauma. Pilots' spines regularly exposed to high Gz may be degenerating more rapidly than normal. The high prevalence of neck pain in flight suggests frequent minor injuries are occurring. The cases in which more severe injuries have occurred may represent one end of a spectrum of in-flight injuries. The circumstances associated with in-flight injury are in keeping with these theoretical mechanisms. Repeated minor neck injuries may be exposing pilots to cumulative trauma and causing their spines, especially their cervical spines, to degenerate more rapidly than individuals not exposed to high Gz.

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CHAPTER 3

MUSCULOSKELETAL SYSTEM AS RELATED TO HIGH SUSTAINED G

3.1 INTRODUCTION:

Exposure to high sustained +Gz (HSG) causes acute neck symptoms in approximately 75% of F-16 and F-18 fighter pilots (109, 191). This incidence rate is far greater than sustained in pilots of earlier generation of F-4 type fighter aircraft who were routinely exposed to considerably lower levels of G. Although these acute symptoms usually involved the soft tissues of the neck, their increased incidence suggests the neck region is at risk in pilots flying these very high G advanced fighter aircraft.

Such acute episodes could be held to herald more chronic changes reflecting repeated HSG exposure over many years of flying. Similarly, spinal degeneration is initially silent without obtrusive symptoms. Only after years of repeated "subclinical insults" do symptoms begin to appear. When symptoms finally develop, they tend initially to be non-specific and similar to the normal effects of aging. The in-flight occurrence of acute neck symptoms suggests the cervical spine in particular is at enhanced risk during HSG exposure. On basic principles, the lumbar spine is likewise at hazard.

Correlation of causative agents and spinal symptoms can be difficult to establish. To establish the relationships beyond doubt in this case would require an extensive controlled study that compares different populations, or a longitudinal study to follow this slowly progressing condition.

Such studies are extremely difficult to design and conduct. Large numbers of subjects are required and control populations are difficult to obtain since similar degenerative changes occur from other commonly found unrelated injuries and aging; where "aging" is greater than 16 yrs. Obviously, these studies are very expensive, politically difficult to manage, and they require substantial resources.

Therefore it would be unwise to undertake such studies without critical review of the literature. Such a review should include information related to spinal disorders of various origins; e.g., various occupations, environments, etc. What follows is such a review that summarizes what is known about musculoskeletal problems of the spine as they relate to the HSG environment. This review is essential in completing the task of this working group; i.e., objectively making recommendations on defining the risk of a lifetime of HSG exposure on the spine.

3.2 HISTORICAL BACKGROUND:

3.2.1. Case Studies

Flight Surgeons have been aware of spinal systems and injuries caused by high sustained Gz for some time. Phillips (147) reported a case of neurological dysfunction resulting from an exposure to +9 Gz in 1959. Awareness of a potential problem has grown as high performance fighters such as the F-16 and F-18 have been developed and become operational. Recent interest began with a case report by Andersen describing an acute neck injury sustained by a flight surgeon while flying a Norwegian Air Force F-16B (8). The Flight surgeon was in the rear seat and had been in control of the aircraft for 10 minutes. After completing a series of basic aerobatic maneuvers, he handed control over to the pilot in the front seat. He then relaxed and turned his head maximally to the left to look for an opponent aircraft. While his head was in this position, he was caught completely unaware by a sudden 8 G climbing turn. After the flight, the subject experienced nausea and neck pain. Clinical examination revealed localized neck pain at the level of C5 and C6, a hypermobile head and cervical column and cutaneous analgesia corresponding to the C7 dermatome. Radiological examination showed a separation of the spinous processes of C5-6 and equivocal evidence of a compression fracture of C6. Anti-inflammatory drugs and physiotherapy successfully treated the injury although the cutaneous anaesthesia took a month to resolve. This case illustrates many of the features of acute neck injuries occurring in flight.

Schall (169) presented eight cases of acute in flight cervical spine injury in F-15 and F-16 fighters. These cases included a compression fracture of C5, a compression fracture of C7, two cases of left herniated C5-6 nucleus pulposus (C5-6 HNP), a myofascial pain syndrome, a fracture of the C7 spinous process and a left herniated C6-7 nucleus pulposus. The first compression fracture occurred during a 9 G pull up and the second while turning the head at 6.5 G. The interspinous ligament injury occurred while the pilot was checking his 5 o'clock position over his right shoulder at 4.5 to 5.5 G. These three cases were all treated conservatively with analgesia and neck collars with eventual recovery and return to flying duties. The first of the C5-6 HNPs pre-

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sented as the onset of parathesia down the left arm at G levels above 6 G. The second was associated with moving the head at 8.4 G. Both of these cases required surgical treatment. The spinous process fracture resulted from an unexpected 5 G pull while looking over the shoulder. The C6-7 HNP was caused by an unanticipated 9 G exposure while the subject was checking his 5 o'clock position. This case also required surgical treatment. These cases reinforce the factors identified by Anderson of high G, head movement or rotated head position and unexpected maneuvering as causing these neck injuries.

Schall (168) has reported a very severe neck injury where a pilot fractured three cervical vertebrae and suffered tetraparesis as a result. This was an unusual case involving a canopy impact in an F-4 during a negative G maneuver. Other rare effects of exposure to high Gz are occasionally reported in the literature including a case of cervical dystonia (spasmodic torticollis) that required treatment with botulinum toxin (38).

3.2.2 Surveys of Acute Neck Pain

Individual injuries such as those described above, along with the appearance of aircraft such as the F-16 and F-18 which are capable of higher onset rates and levels of sustained Gz than previous fighters, have prompted a number of surveys aimed at gauging the extent of the problem of neck injury in flight. Knudson et al (109) reported the results of a comparative study between F/A-18, A-7 and A-4 Naval pilots. Sixty percent of a total of 148 aviators reported neck pain in flight. When the individual aircraft were considered, the F/A-18 pilots had the highest incidence (74%), while the lower performance aircraft had lower incidences of 58% and 30% for the A-7 and the A-4 respectively. Clearly, increasing the capabilities of the aircraft increased the incidence of neck pain.

The subjects responding to the questionnaire in this survey were asked to estimate the severity of their neck pain on a 10 point rating scale. The results of this query demonstrated that the severity of neck pain increases with increasing Gz. The most common head position when neck pain occurred was the "check six position". Of 37 pilots reporting neck injury while flying the F/A-18, 11 were removed from flight status for an average of 3 days. Periods of several weeks were required for recovery in some cases. This survey points to the high prevalence of neck injury in the high Gz environment. Unfortunately, it is not clear what time period is covered. Most likely, the participants in this survey were reporting on life time experiences. The authors suggest reducing helmet weight and a program of neck strengthening exercises should help reduce the number of in flight neck injuries.

Vanderbeek (191, 192) undertook a similar survey in a larger sample (437) of USAF pilots flying the F-16, F-15 and F-5. In his sample, 50.6% stated they had some type of acute injury in the preceding 3 months. In the F-16 pilots, the incidence was 57.5%. When the period examined was extended to a year, the prevalence for the three aircraft types increased to 63.6%. Statistical analysis of these data showed a significant trend in frequency with the F-16 and F-15 having a greater frequency of injury than the F-5. There was also a significant trend in severity of injury with the F-16 pilots suffering more severe injuries than the F-15 and F-5 pilots. This survey also suggests that older pilots are more at risk of severe injuries. This group of pilots again commented that neck injuries occurred while they were moving their heads under G or looking back over their shoulders to "check six". This investigator makes a number of recommendations for coping with the problem including regular neck exercise programs, neck warm-up exercises prior to exposure to G, a gradual return to the high G environment after a layoff and minimizing head movement under G. It is also suggested that head support devices may be necessary if pilots are to be expected to function in even higher G environments.

The Air Forces of other NATO nations have also been concerned with the appearance of neck problems. When the Belgian Air Force replaced its F-104s with F-16s in 1977, its flight surgeons began to encounter cervical spine injuries. In an anonymous questionnaire survey conducted in 1984, 13 out of a sample of 30 pilots admitted to incidents of cervical pain in flight (21). In 1988, 16 out of 30 pilots responded positively to this questionnaire. Overall, about 50% of the pilots surveyed complained of suffering neck injuries every month, 20% reported suffering weekly injuries and 1 pilot admitted to experiencing neck pain every flight. Two of the 30 pilots sampled in both years had to abort their missions because of neck pain. "Neck symptoms" usually occurred at 7 Gz or greater. The pilots surveyed described a variety of strategies to minimize head movement under G including supporting the head using the left hand. In 10 years of F-16 flying, a total of 55,000 hours, no cases of "serious structural damage" to the neck have been reported. Concern over this problem prompted the Belgian Air Force to initiate a screening program in 1984 with

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cervical spine radiography repeated every 5 years.

The controlled environment of the centrifuge has been used to investigate cervical spine problems in subjects exposed to sustained Gz. Two hundred thirty-eight inexperienced pilot candidates from the German Air Force Academy (210) completed anonymous questionnaires after completing centrifuge rides up to 8 Gz. Musculoskeletal problems were reported in 10% of the subjects. Only minor cervical symptoms were admitted by 3.6% of the riders. Obviously, the head motions of these subjects were different from those required of operational pilots. These subjects did not wear helmets; another factor which would have reduced the cervical spine load in these subjects.

Hamalainen studied neck pain among Finnish military pilots (6). This author also sought to establish the prevalence of neck pain in fighter pilots. Forty-eight percent of 360 military pilots responding to the questionnaire admitted to suffering neck pain in flight. Neck pain usually occurred when performing combat maneuvers at acceleration levels between 4 and 8 Gz. The greatest problem occurred in pilots flying the Hawk Mk 51. Neck pain is also a problem in the Swedish Air Force. Forty-three percent of a sample of 39 fighter pilots admitted to suffering neck pain in flight at least once a month, with some pilots experiencing neck pain as often as once a week (83).

Neck pain in flight continues to be a problem. The most recent survey was published by Yacavone and Bason (211) who reviewed data from the Naval Safety Center covering the years 1980 through 1990, looking for reported cases of in-flight neck injury causing at least one day's absence from flying duties. They found only 12 reported cases but did observe, before 1990, it was not a requirement to report neck symptoms from high Gz exposure. In addition to covering the Naval Safety Center data, these authors surveyed flight surgeons asking them to unofficially report the number of cases of G related neck injury seen during a 90 day period. They found a period prevalence of 6.7% over the 90 day period equivalent to a prevalence of 26.8% per year. These rates are much lower than reported by other authors, mostly because only those cases reported to the flight surgeon were counted. Yacavone and Bason (211) also suggest the USN benefited from the earlier experience of the USAF and was able to implement preventative measures when they introduced the F/A-18 and F-16. These measures included a lighter weight helmet and physical conditioning programs. Naval aviators, as a captive population for long periods of time on aircraft carriers at sea, may have better compliance with physical conditioning programs when compared to USAF pilots. Most likely the low incidence seen in this study reflects the general reluctance of pilots to report medical problems unless they are interfering seriously with the pilots' functioning in the cockpit.

3.2.3 Chronic Health Effects of HSG

The published cases of major neck injury and the high prevalence of neck pain in flight raise the question of long-term effects on the musculoskeletal system of exposure to high Gz forces. Several attempts have been made to investigate this question. An early effort to identify long term sequelae of high G exposure, surveyed USAF waiver files for the two years from 1 Jan 1980 through 1 Jan 1982, looking at 27 specific disease categories divided into 4 major organ groups thought to be affected by G exposure (126). Pilots flying tanker, transport and bomber aircraft served as the control group for this study. The only significant difference found between the two groups was for vertebral fractures which, on detailed analysis, were related to ejection and not G exposure. The author of this study does comment that experience of high performance aircraft was limited at the time of the study and a long term prospective study was essential to investigate the question of chronic effects of high G exposure.

A more recent study (65) examined a group of 31 pilots with ages ranging from 23 to 55 years and high performance fighter experience ranging from 240 to 7,200 hours. A combination of clinical and radiographic methods was used to compare the pilot group to a group of age and sex matched controls who were not pilots. Seventy-one percent of the pilots related in-flight neck pain experiences of varying frequencies occurring under similar circumstances to those described in the studies above. The only clinically detectable difference between the pilots and the control group was in neck range of motion, with pilots in the age group 30-39 years showing significantly reduced lateral neck flexion. Radiography of the cervical spine was used to examine vertebral body heights, paravertebral soft tissue, degree of lordosis, osteophytic spurring and intervertebral disc narrowing. Of these parameters, there were significant differences in the degree of osteophytic spurring at C5 and C6 between pilots and controls in the age group 30-39 years and smaller but still significant differences in the age group 40-55 years. Disc space narrowing was significantly greater in the pilot group in all age groups. The authors of

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this paper conclude that pilots do suffer an increased rate of degenerative change in the cervical spine compared to controls.

The study above suffered from a number of problems. The first of these was the control group at all ages was smaller than the subject group. In the age range 20-29 years, there was only one control subject making comparison impossible. To make up for this, a published study of radiographic findings in a large group of asymptomatic subjects was used as a control group for the radiography, although the paper is not always clear whether the selected or the published control group was being used with some of the comparisons. Five of the subjects in this survey had been involved in an aircraft mishap involving either an ejection or forced landing. These subjects were not excluded from the analysis. The forces encountered during accidents and ejections apply substantial loads to all levels of the spine and have a known potential for spinal injury, possibly confounding attempts to isolate high Gz as a source of injury. If these subjects had been excluded, it is possible that some of the statistics might no longer be significant. The other major problem with the above investigation is the interpretation of the radiographic images. Deciding whether a disc space is narrowed or there is significant osteophyte formation calls for a subjective judgment on the part of the radiologist interpreting the images. In Gillen and Raymond's study (65), two radiologists differed in their interpretation in up to 8% of the films. The paper does not indicate how these differences were resolved.

The only other published study that has investigated chronic damage to the cervical spine in pilots was published in 1993 by Hamalainen et al (80). This study investigated a group of 12 senior fighter pilots from the Finnish Air Force with ages ranging from 35 to 37. They were selected because their Gz exposures were the highest among Finnish Air Force personnel in the decade preceding the study. The pilots were compared to an age matched control group of 12 Finnish Air Force ground personnel. Questionnaires established that the control group had similar smoking and exercise habits. Both groups had similar histories of non-flight related neck pain over the previous 12 months. Low field Magnetic Resonance (MR) was used to produce sagittal sections through the cervical spine. Disc degeneration was classified as grades 1-6 depending on the degree of posterior nuclear extension. Overall, the median level of disc degeneration (grade 2) was significantly greater for the pilots than the control group (grade 1). When the individual discs were examined, 88% pilots had degeneration (grades 1 to 6) at the C3-4 level compared to 64% of the controls. There were no differences at any other level. When the degree of disc degeneration was subdivided into mild (grades 1 and 2), moderate (grades 3 and 4) and severe (grades 5 and 6), there was again a significant difference between pilots and controls at the C3-4 disc (pilots 88%, controls 36%). There were insufficient severe cases for statistical analysis and no differences in the mild category. Two researchers examined the MR images together and reached a consensus on grading of disc degeneration. The order of the films was changed and the two researchers read them again a few hours later. The Pearson's coefficient of correlation between the two readings of 0.69 was considered good; thus suggesting that exposure to high Gz can cause degeneration of the intervertebral disc. However, the paper does not indicate which of the two readings was used for subsequent analysis.

3.2.4 Lumbar Spine

At present, researchers concerned with the effect of high Gz forces on the spine have focused on the cervical spine, largely because of the high prevalence of in flight neck pain and the published case studies of major neck injuries occurring in flight. The rest of the spine has been neglected except for the problem of ejection. High Gz can injure the lower back. Two cases of ruptured intervertebral discs in the lower back were reported by Shaw in 1948 (178). The first of these occurred in a P-38 that executed an emergency 9 G pull up to avoid ground collision. The subject experienced acute back pain on getting out of the aircraft and developed the symptoms and signs of a herniated L4-5 disc, later confirmed with a myelogram and at surgery. The other case was of a civilian test pilot who experienced an acute onset of low back pain at 5 G in an F-4 F. He too developed the signs and symptoms of a ruptured intervertebral disc, but, as he was treated conservatively, the diagnosis was never confirmed. In both of these cases, the subjects were in a flexed position during the high G and this position was considered instrumental in producing the injuries.

Harms-Ringdahl et al (83) asked about the occurrence of back pain along with questions about neck pain in their study published in 1991. They report 26 % of their sample of Swedish Air Force fighter pilots suffered low back pain in flight. Voge and Tolan (195) investigated the occurrence of back-pain among a group of 20 centrifuge sub-

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jects who had regularly ridden at levels up to 9 G. They compared this group with 20 similar research subjects who did not participate in centrifuge experiments. There was a lower incidence of back problems in the centrifuge group. It is possible that this observation is a result of the selection procedures for the centrifuge panel. Subjects with a previous history of back problems are carefully excluded from the panel. In order to study a larger group of subjects, these authors investigated the disability rates for all separating or retiring USAF Air Force Officers for the years 1972 through 1991. They were unable to find any differences between non-rated officers; tanker, transport and bomber rated officers; and high performance fighter rated officers. In fact, the disability rate for both types of rated officers decreased after 1985 compared to the non-rated officers. This study did not support the hypothesis that exposure to high G causes back problems. These authors recommend a prospective study of all rated officers be conducted and the separation physical examination include a detailed back history and examination.

The cervical spine should not remain the exclusive focus of investigations of the effect of high Gz on the spine. High G forces may accelerate the normal degeneration process at all levels. One of the problems in investigating the lumbar region is that back problems are extremely common in the general population. A subject group of 20000 or greater may be needed if the effect of high G on the lower back is to be separated from other sources of back problems (194). The ability of high G forces to injure the neck is evidenced by the high incidence of neck pain in flight shown in existing studies. There have been only three published attempts to investigate the long term effects of high G on the cervical spine. These investigations have illustrated the many problems of research in this area. Nonetheless, these studies do suggest that high G forces do promote degeneration of cervical spine structures beyond that normally associated with aging.

3.3 RISK FACTORS FOR LUMBAR SPINE DISORDERS

Back injury or pain is extremely common in industrial populations. For example, in the United States, it is the fourth most common complaint among adults with acute symptoms (114), makes up about 20 percent of all occupational injuries (129), is the leading cause of disability in those under 45 years of age and the third major cause of disability in general (exceeded only by heart disease and arthritis) (68, 123, 133). Most injuries are minor (sprains and strains) and patients recover within one month (15, 19, 31), but recurrences are common in that up to 70% of those affected will experience at least one recurrence (1, 148, 204). Men and women seem to be affected equally as are white collar workers and laborers, although these issues are controversial (31, 61, 129, 131, 204, 215). Low back pain is most frequent between 35 and 45 years of age (31, 55, 129, 215). Sixty percent of retired workers reported having experienced low back pain in the workplace (before retiring) of sufficient severity to seek medical attention (164). Low back pain is frequently the most expensive item in total overall disability compensation payments (165). Some authors estimate that 70-90% of all individuals will eventually suffer back problems of some sort (31, 61, 129, 204). The prevalence of back problems increases with age and also seems to have a relationship to an individual's activities and occupations. The majority of acute back pain sufferers have no related lesion demonstrable on (positive in as few as 1%) radiological examinations or with sophisticated clinical tests (61, 134).

A clear understanding of the causes of back and neck problems remains elusive. The problem is difficult clinically, as structural causes of back and neck pain are not often identified in these patients, while extensive degeneration is often found in asymptomatic people.

The economic consequences of spine problems have prompted a considerable research effort into the etiology and biomechanics of musculoskeletal disorders of the spine aimed at preventing workplace injuries and improving treatment.

Hildebrandt (89) has reviewed the published literature and identified risk indicators for low back pain that appear consistently in published surveys. This author found 24 work-related factors which were regarded as risk factors for low back pain. Of these, 8 could be considered as generally accepted (in that they were mentioned by at least three sources). These were: heavy physical work, static work load, prolonged sitting, dynamic work load, heavy manual handling, heavy or frequent lifting, trunk rotating, pushing/pulling and vibration. There were 55 individual factors mentioned by at least one of the sources. Hildebrandt reduced these to six generally accepted risk factors; 1) constitutional: age, relative muscle strength, physical fitness; 2) medical: previous back complaints, unspecified psychosocial factors; and 3) other: work experience. Aviators are exposed to a limited number of the risk factors cited by Hildebrandt (89). The most

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important of these relate to prolonged sitting. Riihimaki (157) reviewed these generally accepted risk factors in more detail. Of interest to the aviation community is motor vehicle driving is positively associated with low back pain, sciatic pain and herniated intervertebral discs. Whole body vibration in the seated position may be responsible. Although the forces and vibrations experienced in high performance aircraft differ from those seen in motor vehicles, there is a possibility they may be increasing the risk of low back pain in pilots. In vivo pressure measurements of disc pressure (131) have demonstrated the load on the intervertebral discs is greatest in the seated position. Tilting the seat back, providing lumbar support, and the use of arm rests reduce these pressures. Fighter pilots sit on an ejection seat which provides minimal lumbar support, and with the exception of the F-16, have seatback angles close to the vertical. The lumbar and thoracic spinal structures are required to support the loads imposed by high G in postures that are not optimal. Our current knowledge of the etiology and biomechanics of low back pain suggest pilots of high performance jets have increased risk of low back disorders.

3.4 RISK FACTORS FOR CERVICAL SPINE DISORDERS

Although musculoskeletal problems of the neck are common, there is less published information on the etiology of these disorders. Kelsy et al (108) found, other than age and sex, the most important risk factors for prolapsed cervical disc were cigarette smoking, frequent diving from a board and lifting heavy objects. Driving or riding in automobiles, operating vibrating equipment and possibly playing golf were associated with an elevated risk, but these risks were not statistically significant. The most frequently prolapsed cervical discs were C5-6 and C6-7. Hagberg (73) was able to find only a few reports on the prevalence of degenerative changes of the cervical spine in different occupational groups and concluded that occupational stress as a factor in degenerative joint disease remains obscure. He goes on to suggest there is strong support in the literature that occupational muscle stress may cause disorders of the neck and shoulder. The stresses associated with constrained working postures and repetitive arm movements are potent causes of neck and shoulder disorders. In a later article, Hagberg and Wegman (74) reviewed the literature hoping to establish the association and impact of occupational exposures on diseases of the shoulder and neck. These authors were hampered by the lack of detailed job descriptions in many of the articles they considered. Meat carriers, dentists, miners and heavy workers had higher risks for the development of cervical spondylosis (degenerative disease of the cervical spine generally diagnosed from radiological changes). The fact that meat workers partially carried their loads on their heads and miners' neck loads were increased through wearing helmets, were considered to support the hypothesis that cervical spondylosis is caused by high loads on the spine. Dentists are frequently required to hold their heads in extreme positions which may increase their cervical spine loads. Civil servants were found to have increased risks of cervical disc disease which was hypothesized to occur because their work postures required extreme forward flexed positions of the cervical spine. Tension neck syndrome (neck stiffness because of fatigue, with neck pain or headache) occurred frequently in keyboard operators. Hagberg (73) postulates extended periods of static contraction of the neck and shoulder muscles may be responsible for this syndrome.

The high prevalence of in-flight neck pain and the case studies linking neck Injuries to in-flight forces imply that the cervical spine injuries seen in pilots may represent a unique occupational risk having little in common with other occupational groups. Hamalainen et al (80) attempted to find determinants of Gz related neck pain by following a cohort of 27 male fighter pilots. The only individual characteristic having a relationship to in-flight neck pain was the frequency of muscle endurance training. The other factors (strenuousness of work, job satisfaction, psychological distress, smoking habits and anthropometric measurements) had no correlation with in-flight neck pain. The ability of African laborers to carry loads of 200 lb (90 kg) on their heads demonstrates that the cervical spine is capable of carrying very high loads as studied by Scher (170). Carrying these loads does not seem to predispose these workers to premature osteo-arthrosis of the cervical spine. Assuming the head and helmet weigh 6 kg, the static load carried by the cervical spine at 8 G would be 48 kg (76); while at 9 G, it would be 54 kg, well within the load carrying capabilities of Scher's laborers.

3.5 METHODS FOR INVESTIGATING HEALTH EFFECTS OF HSG

The reports in the literature to date leave no doubt about the ability of high Gz to cause neck pain. The few reports relating such acute insult to long term, chronic degeneration of the spine are suggestive, but not conclusive. There is a clear need for continued research on: 1) acute

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injuries in flight and 2) the potential long term consequences of exposure to high Gz. The most urgent need is to establish whether or not spinal degeneration is accelerated in pilots exposed to high Gz. There are two basic approaches to investigate this relationship. The first is by cross-sectional studies of the type which have already been reported. They have established the prevalence of neck symptoms in-flight. They are less successful in establishing the chronic effects of Gz exposure. The investigations reviewed before in this chapter, demonstrate many of the problems. When existing records, such as waiver files or exit medicals, are used as a data source, they may be subject to considerable underreporting. The exit medical examination is a very general medical examination conducted by many different doctors without specific instructions to assess the cervical and lumbar spine. These medical examinations will only find obvious deficiencies and, to a researcher, suffer from a lack of standardization in the clinical assessment. Waiver files underreport the incidence of spinal problems because there has not been a requirement for flight surgeons to report such problems. Until there is a severe problem, aircrew do not usually report to the flight surgeon. This type of study should continue, but can only be successful if individual flight surgeons are required to examine the neck and back in detail, and if guidelines are issued standardizing the clinical examination of the neck and back. The standard doctor's office clinical examination is a very insensitive method for detecting degeneration of the spine and, unless particular care is taken, does not assess function accurately.

Imaging of the spine is a more sensitive method of detecting degenerative changes, but also suffers from many technical problems. If a cross-sectional study is carried out using radiography, the subjects are exposed to an unnecessary x-ray dose. When x-rays are not used for treatment and diagnosis, ethical problems arise. Magnetic Resonance (MR) scans are not considered to have any adverse health effects and are the imaging modality of choice for studies of the type discussed earlier. Unfortunately, while they demonstrate soft tissues, such as the intervertebral disc, bone is not imaged as well. The changes associated with degeneration of the spine require human interpretation of the images. Such interpretation is subjective and there are often disagreements when different individuals report on the same image. While certain changes seen radiographically are accepted as associated with degeneration of the spine, there is little correlation between radiographic findings and clinical findings. These issues are discussed in more detail in the section on imaging. The studies claiming to have shown degenerative changes in the cervical spines of pilots exposed to high Gz used imaging methods, and indicate that these methods should be part of the investigation of the chronic effects of high Gz on the spine.

A cross-sectional study needs to compare the subject group to a control group in order to establish the significance of experimental findings. Selection of good control groups is extremely difficult. The studies on the prevalence of in-flight neck pain have compared pilots of aircraft of differing performance and have successfully demonstrated an effect of aircraft performance. In other studies, ground crew have been used as control groups. Although ground crew are not exposed to high Gz forces, a better control group would be another pilot group that is not exposed to high Gz. The studies using tanker, bomber and transport pilots as a control group have failed to detect differences between this group and pilots of high performance aircraft. A low G group of subjects remains the ideal control group for comparison with pilots of high performance aircraft.

The ideal method of investigation is the longitudinal study. Voge and Tolan (195) concluded that a prospective study was the best way to identify chronic back problems induced by Gz. The problem with such studies is they take a long time to yield results, especially with the type of problem dealt with in this section, which takes years to develop. There can be a high attrition rate among the members of the study and control groups, reducing the significance of the final results. The long term involvement of the investigators in longitudinal studies is expensive and the delay in producing usable results delays the introduction of remedial measures. However, when measures are introduced to combat the chronic effects of high Gz on pilots, a prospective study is the best method of measuring treatment effectiveness.

There are other methods of obtaining data regarding degeneration of the spine. Pilots killed in aircraft accidents offer a unique opportunity to obtain information not available by other means. Dissection of the intervertebral discs, vertebral bodies, and spinal ligaments would enable changes in structure and biochemistry to be investigated. The numbers involved are small but offer a unique source of information. To obtain this type of information, pathologists conducting post mortems would have to be instructed to collect the necessary material and establish a test protocol to

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include detailed neuropathological review.

Physiological studies of neck function in flight have yielded useful information. Electromyography (EMG) can be used to measure muscle performance in flight. Hamalainen and Vanharanta (78) used this technique to measure the activity of the cervical erector spinae with the head in different positions at various Gz levels. He found some individuals reached 100% of maximal voluntary effort with the head rotated at 4 G. Hamalainen (77) also used this technique to measure the effect of different helmet weights on the cervical erector spinae at different Gz levels. Although he only used two subjects in this study, he was able to demonstrate wearing a lighter helmet did produce lower neck forces at high Gz levels. Linder et al (115) have also reported using EMG in flight. Studies of this type using larger numbers of subjects could produce useful information on the physiology of neck function at high G levels that could validate the muscle tensions predicted by mathematical models and in turn serve as a useful input to those models.

The occurrence of neck pain in flight is well established. The functional significance of in-flight neck pain is not. Finding a reliable objective method of functional assessment of the spine is extremely difficult. A variety of techniques have been used in the past to measure range of motion of the neck including radiography, cineradiography and photography. The standard clinical method to assess joint motion is a protractor (known as goniometry). The use of goniometry for measuring head motion has been reviewed by Defibaugh (48). He proposed a pendulum goniometer attached to a mouth piece as a reliable device to measure head motion in all three planes. A more recent method found to correlate well with measurements made using cineradiography was reported by Alund and Larsson (7). This method consisted of a number of electronic goniometers built into a system of rods attached to the top of the head at one end and to a point near the shoulder at the other. With the torso restrained, this apparatus was able to produce reliable three dimensional measurements of joint motion. These authors make the point that neck injuries are often associated with impaired function rather than detectable morphologic lesions and that precise objective assessment of the neck is important to record initial impairment and track recovery. Marras et al (121) have added velocity and acceleration to the range of motion measurements taken from patients with low back disorders. They found velocity and acceleration were more sensitive indices of functional capacity, with acceleration the most sensitive. This approach might be useful in the neck. Range of motion is only one aspect of spine function. Muscle strength measurements are also useful measurements. Isometric extension strength has been shown to be a reliable measurement in both the cervical spine and lumbar spine (69, 113). When these measurements are taken over the full range of motion of the neck or lumbar spine, the graph of strength against extension should be linear. Deviations from linearity are usually associated with functional abnormalities. Isometric extension strength has been used by these authors to track recovery from spinal injuries. Harms-Ringdahl et al (83) found neck mobility and strength did not correlate with neck pain originating in-flight while neck flexor and extensor endurance did. Testing with sustained low neck muscle resistance or maintained rotated neck positions frequently provoked neck pain in those pilots reporting in-flight neck pain as a weekly occurrence. Very little information apart from this report is available on the functional significance of in-flight neck pain. Research in this area is hampered by a lack of techniques for functional assessment of the neck. This area needs more effort, firstly to identify suitable measurement techniques and secondly to collect data on pilots with neck pain.

3.6 TREATMENT AND PREVENTION OF INJURIES ARISING FROM HSG:

3.6.1 Limit High G Exposure Time:

Knowing that high Gz can cause chronic health problems is important but must lead to methods for reducing these effects. The most obvious method is to reduce the total lifetime exposure to high Gz forces by allowing pilots to fly only a limited number of tours on high performance aircraft. This approach has disadvantages. It does not allow the armed services to fully amortize their investment in training and will not eliminate acute in-flight neck pain. Those pilots who succeed in training to fly high performance aircraft have immense pride in their achievement and are likely to resist moves to limit their flying time. Ideally, techniques that prevent spine injury should be devised that allow pilots to continue to fly a full career on high performance aircraft.

3.6.2 Pilot Selection

There are a limited number of approaches to this problem. The earliest point of intervention is before training starts, by screening out individuals with existing abnormalities and a predisposi-

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tion to degenerative changes in the spine.

History is the key. Full neurological as well as past spinal, social, and family histories are as good a screening tool as any other examination yet introduced at a fraction of the cost, particularly if attention is plied to the risk factors spelled out in Table 3-1.

Caution has to be exercised in applying brute technology to selection. Individual prognosis and routine screening have a poor track record. Careful surveillance of existing aircrew, the results of which are published and practical exposure to and familiarity with present and future operational realities among medical members of selection panels will remain the most certain assurance of successful aircrew selection.

Kazarian and Belk (104) proposed standards for acceptance of candidates for aircrew training based on biomechanical investigations. They list a number of conditions visible radiographically that should disqualify prospective trainees. Their main concern was that certain disorders of the spine would be aggravated by ejection and exposure to high Gz. The Norwegian Air Force has instigated a program of radiological spine screening in aircrew trainee applicants. They found on average 2.27 diagnoses per x-rayed spine (9). Despite considering films where the findings were in doubt or borderline, as normal, they rejected 25 of 232 applicants. The Belgian Air Force, concerned about degenerative disease of the spine in their F-16 pilots has initiated a program of regular screening with cervical spine x-rays every five years since 1984. The results of this screening program have not yet been published. Subjects selected as candidates for the Armstrong Laboratory centrifuge panel at Brooks Air Force Base, Texas are screened in a similar way to aircrew candidates. The spine is examined with a complete series of spinal radiographs (200). Eight of 81 candidates were rejected as a result of spinal abnormalities considered disqualifying by Kazarian and Belk's report (104).

Recently MRI scans have been used to screen for spinal abnormalities in this group. Burns et al (29) reported that 77% of 22 male centrifuge subjects and 74% of 19 age matched males used as a control group, had spinal disc abnormalities. One of the problems in this study was comparison of a first and second reading by one of the radiologists demonstrated 23% agreement and 77% disagreement. Similarly, comparison of the same films read by two different radiologists demonstrated 11% agreement and 89% disagreement, highlighting the subjectiveness of interpretation of the results of these investigations.

Pre-employment screening using radiography in occupations at high risk of low back pain has been controversial. These x-rays have been poorly predictive of future low back pain and have not been shown to offer any benefits in industry (64). In selecting candidates for flight training, we can tolerate false positives in screening for spinal abnormalities leading to rejection of some candidates who might not develop spinal problems. However, if the use of x-ray or MRI screening becomes wide-spread, its efficacy should be evaluated.

Despite the intense physical challenge hyper-G ACM presents, the primary military requirement for the intellectual integrity, capacity, dexterity and flexibility to undertake successful defense will remain. The sometimes conflicting criteria for the intelligence to evolve tactics and strategy and for the physique to exploit them will continue to test selectors.

3.6.3 Physical Training

3.6.3.1 History

In modern military practice, the relationship of posture to subsequent satisfactory military, albeit infantry, performance even in a selected population seems to have been recognized first in the basic training of the Preobrazenskaya Regiment for Peter Romanov. Lordosis or rather "correct military bearing" in the language of the day was not only advantageous in maintaining orderly appearance on parade, but proved essential to the unfaltering, automatic wearing of a 56 lb backpack without tactical impediment on campaign. This lesson was not lost on Frederick of Prussia after the unsatisfactory performance of his original Guard. Every drill sergeant knows the first requirement is lordosis and a balanced head. In practice, the first principles of high -Gz operation have unwittingly been taught by the armed forces for almost 300 years. Though Ms BEATON, "carriage", deportment and finishing schools are out of fashion, a return to civilian emulation has recently been proposed (20).

3.6.3.2 Review of the Relationship Between Physical Fitness and Spinal Symptoms

Suggestions that neck muscle strengthening exercises reduce the occurrence of in-flight neck pain are a recurring theme in all of the reports on this subject. The relationship of muscle strength

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and physical fitness to occupational disorders of the back has also been investigated by several authors. Specific exercise and muscle strengthening programmes have been used in the treatment of back and neck disorders. Chaffin et al (36) found a worker's likelihood of sustaining a back injury increases when job lifting requirements approach or exceed the strength capability demonstrated by an individual on isometric simulation of the job. This report recommends strength performance criteria should be used in selecting employees for jobs placing high stress on the back. Cady et al (33) demonstrated a graded and statistically significant protective effect for added levels of fitness and conditioning on the occurrence of back injuries in firefighters. Strength and fitness may alter the way in which musculoskeletal components of the spine fail. While a larger portion of miners present with low back pain when compared to non-miners, fewer of the miners had criteria for disc protrusion. Porter (150) hypothesizes heavy manual work strengthens the spine, restraining encroachment of a disc protrusion into the vertebral column. The role of fitness is not as clear in a large (3,020 subjects) study reported by Battie et al (19). Their subjects completed an extensive questionnaire covering cardiovascular risk factors, past medical history and previous back problems. Maximal oxygen uptake measurements were completed in 2,434 of these subjects. These measurements were not predictive of future back injury. In fact, consistent with many other studies, the only factor predictive of back injury in this prospective trial was a history of smoking. Porter (151) examined the cadaveric spines of young men killed in road accidents. They found the compressive strength of spines from subjects over 18 years of age increased with level of physical activity and, in some cases increased to such an extent, the disc prolapsed before vertebral failure. Riihimaki (157) concluded general physical fitness, measured by aerobic capacity, and trunk muscle strength did not predict future back injury.

Despite a lack of consensus on the relationship between physical fitness, muscle strength and back problems, physical therapy is one of the major conservative approaches to treatment of musculoskeletal problems of the spine. The "Back School Program", emphasizing posture and using a regimen of stretching and strengthening exercises tailored to individual patients, was recently reviewed in detail (201). Lumbar strengthening, using a device designed to specifically strengthen the isometric lumbar extensors, has been shown to reduce symptoms in low back pain sufferers as compared to an untreated control group. The treated group reported less physical and psychosocial dysfunction (158). Specific training regimens and equipment can also increase isometric cervical extension strength (113). This training was able to reduce pain and increase range of motion in 90 patients, reported by Highland et al (88). Unfortunately no control group was included in this study.

There has been very little investigation of the effects of training regimens on in-flight neck pain. Harms-Ringdahl et al (83) found neck flexor and extensor endurance was correlated with neck pain in a group of 39 Swedish Air Force fighter pilots (discussed above), but neck range of motion and strength were not. Hamalainen et al (79) used a questionnaire to try to identify determinants of in-flight neck pain in 27 male student fighter pilots. The pilots who engaged in frequent muscle endurance training (although the details of this training are not described) suffered less in-flight neck pain. Grip strength and isometric neck muscle strength did not correlate with in-flight neck pain. The wide-spread use of muscle strengthening to treat back problems and the growing use of cervical muscle strengthening to treat neck problems suggest these methods may be useful in fighter pilots. Many of the pilots who suffer regular in-flight neck pain episodes added comments to their questionnaire responses to the effect that they were only able to fly if they performed a set of neck warm-up exercises before flight. The two studies cited above do not clarify whether muscle strengthening and endurance exercises would be beneficial. The biomechanical investigations demonstrating the neck muscles are functioning close to their strength limits at high Gz indicate increasing neck muscle strength should be beneficial. A neck strengthening program would fit neatly into the isometric muscle strengthening program currently used to improve tolerance of the cardiovascular system to high Gz. The introduction of a neck muscle strengthening program should be monitored to establish its efficacy.

3.6.3.3 Present Aircrew

Aircrew education to cover the present problems, the habitual practice of lordosis and head balance wherever possible, and the customizing of present seats to the individual is feasible and can be introduced immediately. This effort will make the best use of present equipment and minimize induced morbidity to that imposed by present configurations. This is a duty of care.

3.6.3.4 Future Aircrew

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Training for future HPA operations requires the determined establishment and then continuous maintenance of lumbar and cervical lordosis. No fledgling HPA ace will take kindly to this apparently anachronistic reawakened interest in the drill square unless the purpose is explained and the neurological and spinal factors involved in the successful exploitation of maximum manueverability are understood ab initio. Fortunately, this is the easiest and cheapest of the necessary reforms in attitude and practice, while an improvement in posture is important to every member of the armed forces as it should be to the general population at large.

Early familiarity with and full exposure to the whole ±Gz envelope should follow. Use of HPA or simulation with centrifuges and virtual reality is expensive when daily progressly increasingly high Gz experience and conditioning is required. An alternative is the use of low cost unlimited class aerobatic aircraft. They would enable fighter aircrew in training to gain experience and confidence throughout the full flight envelope as well as maintain G conditioning in established fighter pilots.

3.6.4 Physical Therapy Post HSG

The pilot of HPA can be compared with professional athletes of physically demanding competitive sports; e.g., American football, baseball, basketball, etc. Support programs for these athletes include a professional sports trainer and a doctor; often, a doctor of Osteopathy or a specialist in physical (sports) medicine. It is felt that these athletes would not be able to compete on a regular basis without the support of these physical therapists. Immediately following a game, trainers "rehabilitate" these athletes with body manipulations, massages, etc. Many of these manipulations involve the spine, particularly the cervical and lumbar regions. Flight surgeons at bases for HPA report requests for similar treatment by fighter pilots after HSG exposures; particularly from flight surgeons who are experts in musculoskeletal manipulation. Post-flight physical therapy may prevent the manifestation of underlying spinal degeneration. Providing a training room with skilled physical therapists for all squadrons of HPA could be beneficial for preventing chronic types of spinal disorders (159).

3.6.5 Regular High G Flying Exposures

Despite the major contribution which simulation, centrifuges and environmental trainers can make, there is no substitute for air time. High -G conditioning and adaptation require constant exercise throughout the Gz envelope which can only be provided satisfactorily in the air. Financial restriction being what it is, the use of unlimited aerobatic aircraft as low cost HPA surrogates is now an effective training option. Progressively increased exposure to high Gz over weeks should be the norm. Once established, the adaptation which high ±Gz tolerance represents requires constant and continuous practice. After even short periods off flying, a return to the associated autoregulatory adaptation, especially to high -Gz, takes several painful days of high G exposure to redevelop.

3.6.6 Equipment Improvements

Though improvements in helmet design, construction and materials to lighten neck axial loading have been made, no attempt has been made to improve pilot posture in general or neck biomechanics in particular by removing, replacing, re-contouring or re-positioning the ejection seat headbox, despite the limitation this structure imposes on rearward view in aircraft dedicated to all-round vision. Headbox redesign could allow a "maximum G head park" position for the helmet in full head and neck extension. However, the Eurofighter has incorporated a twin gun design in the ejection seat, allowing the headbox to be moved back, improving pilot head mobility.

Protection against ejection injury, in fact, led to suggestions for head support devices. Several proposals were outlined by Mattingly et al (122) using neck bellows and cables. A prototype was built. The problem with these devices was that although they reduced the load on the neck during ejection, they did so at the cost of restricting head mobility. The analysis reported by Raddin et al (154) also proposes a device that would provide an alternative load path to reduce neck loads when control of the head is lost under G. This study was theoretical and did not progress to building a prototype. Head support devices may be essential if pilots are to function at higher Gz levels than those seen in current and proposed fighter aircraft, but useful systems have yet to be devised. Helmet design offers the potential for reducing neck loads by reducing the weight of the helmet. Unfortunately, recent trends toward lower helmet weights may be reversed by the addition of helmet mounted displays which increase the weight of the helmet substantially. These devices may be a liability at high G and during ejection. Another approach to reducing neck load is to reduce head motion under G. The complexity of the information

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capable of display using up to date technology is increasing steadily. Improvements in display techniques may allow the presentation of the three dimensional information needed by a pilot maneuvering at high G in a manner that does not require head movement. Improving weapon systems with the ability to acquire targets off bore-sight could also reduce the amount of aircraft maneuvering and head movement needed during an engagement.

TABLE 3-I: RISK FACTORS FOR BACK DISORDERS

1. Predictive Risk Factors:

HISTORY	EXAMINATION	RADIOLOGY
Age	Poor posture	Degenerative disc changes
Frequent lifting (especially w/poor posture)	Obesity	Thinning of an intervertebral disc space
Prolonged sitting	Unequal leg length	Pars interarticularis defects
Family history	Low proprioceptive ability	Generalized exostosis
Poor flexibility		Hypertrophic arthritis
Boredom at work		Unilateral sacralization of either 5th or 6th lumbar vertebra
Vulnerability to stress (e.g., frustration and workload)		Old healed fracture with moderate to severe deformities
Unfitness		Fusions
Excessive exercise		Previous history of disc surgery
Exposure to vibration		
Smoking		
Low self esteem		

2. Non-Predictive Risk Factors:

	Height	Normal back
	Weight	Bilateral sacralization of 5th lumbar vertebra
	Overall strength	Lumbarization of 1st sacral vertebra
	Equal limb length	Centres of ossification on vertebral body margins
		Mild to moderate Schmorl's nodes
		Spondylolisthesis (controversial)
		Spondylosis (controversial)
		Transitional lumbosacral vertebrae
		Sagittal or assymetrical lumbosacral facet joints
		Scheuermann's disease
		Minor scoliosis (<60°)
		Lumbar lordosis (<70°)
		Spina-bifida occulta

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CHAPTER 4

IMAGING'S CONTRIBUTION TO THE INVESTIGATION AND MONITORING OF THE EFFECTS OF LONG TERM, REPEATED HIGH SUSTAINED +GZ (HSG).

4.1 INTRODUCTION

Increasing high performance aircraft (HPA) agility, the associated technology (high +Gz, helmet mass, ejection seat and headbox design), and the need for extreme head and neck mobility subject the head, neck and spine to enhanced mechanical stress. In operational terms, the spine is a task-environment related "weak link". The problem is complicated by the fact that all adult humans will eventually experience spinal degeneration with intervertebral disc materials aging and the complications of intervertebral space narrowing (spondylosis) unless active counter-measures are taken. Most people will experience symptoms at some time. Apart from the acute hazard posed to the kyphotic spine by HPA operations, there is understandable concern that increased exposure to +Gz might accelerate the normal spinal degeneration which we all suffer from puberty onwards. Aircrew spinal images can therefore be expected to be abnormal, like those of their peers. The problem for surveillance in general and imaging in particular is the requirement to demonstrate differential change in an already changing subject in which there are wide variations on the norm and no published long-term prospective studies.

In these circumstances, investigation has by tradition been targeted, directed by the clinical requirements of the individual patient and interpreted in the light of the clinical findings. Imaging is used as a tool rather than a "free-standing", independent test. Imaging is selected on the basis of clinical impression. Choice of imaging modality is influenced by anticipation of the likely result. Whilst the clinical intention, at the end of the day, is to "treat the man not the scan".

In HSG surveillance, the objectives of the exercise would be different. Imaging is used in the conventional fashion in symptomatic aircrew. The novel requirement is to define individual status and suggest initial prognosis in the asymptomatic population and then monitor individuals with and without the benefit of various stratagems to establish the spontaneous evolution or natural history of spinal degeneration under HSG, together with the effects, or lack thereof, of interventions (such as the restoration and maintenance of the lordoses, removing the head box, etc). The investigation may (hopefully will) be of benefit to the individual investigated, but this cannot be assured. In this scenario, the potential for mischief caused by inexact investigation and Bayesian reality is protean. The potential for good and ill is further compounded by the near-universal demonstration of degenerative changes in the target population and the absence of a clearly defined entity which could be stigmatized as "high-G spine". Imaging surveillance would be operated in a manner akin to population prognostic screening, in which the extensive experience to date has been disapproving.

Imaging of the HPA community is of great academic interest as they represent a population subject to an overall increased adult life G-exposure of <80%. Their enhanced (if intermittent) axial loading could provide further insight into the mechanics of spinal degeneration and it could identify a number of individuals who might on review be considered at enhanced risk of accelerated degeneration or actual acute spinal element failure under increased spinal load.

But before instituting such a program, a number of basic questions have to be addressed:

1. "Non nocere". Can individuals be assured that no harm, or more good than harm will come to them as a result of their participation?

2. Conflicting priorities in the Duty of Care:

    a. What if the program throws up anomalies which would not have become manifest in the normal way without the new program? Should the pilot be grounded and loose his career?

    b. Should there be a waiver that participation in the program will under no circumstances be turned to the individual's career disadvantage? Without a waiver, cooperation will be minimal and every effort, not unreasonably, will be made by individual pilots either to obscure anomalies which might hazard their ambitions or to maximize and distort them to skew the investigation to some personal advantage.

    c. It is important to establish that until the conclusion of the program, and only then if the findings are that policy should be changed, the aviation medical "rules" will not be changed. The "goal-posts" stay where they are. This does not prevent confidential individual discussion and advice as the individual pilot or his family's clinical interest dictates.

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3. There will be a desire, possibly a compulsion to apply any operational lessons as soon as they are detected. To ensure that early interpretations are correct rather than fallacious the prospective and statistical dimensions of the study must be powerful enough to accept significant variations in the practice both of aircrew and their controls (for example, improved posture and paraspinal tonic muscle mass). The alternative becomes a prospective case study series with lesser but possibly more realistic and practical statistical pretensions. This would be no less important, but prudent prospective surveillance and review is not the same as a controlled study.

4.2 BASIC PROBLEMS

What are we looking for? (1) an enhanced risk of or potential for catastrophic failure? (2) a related chronic progressive degeneration? (3) enhancement, acceleration or exacerbation of a naturally occurring process? or (4) some totally-unforeseen circumstances? That is "shotgun" research, shooting into the dark in the hope that a target might present itself.

In the spine HSG operations trespass beyond a number of normal +1Gz human failure boundaries (such as the load performance of the lumbar discs already compressed in lumbar kyphosis). This may be enhanced by missed or occult individual weaknesses (such as pars interarticularis defects) which by the end of adolescence have developed in >5% of the normal population (60). To date, acute failure has been limited to the ejection case. In the +9Gz generation aircraft rather than the development of a "High-G Back" syndrome, radiological appearances have been compatible with a possible enhancement of the normal process of spinal degeneration with age, compounded by a variation of pattern with maximum stress being experienced at C3-4 rather than the more usual C5-6 level (80). This is in keeping with enhanced upper cervical flexion/extension activity in a basic posture of enforced cervical kyphosis, enforced that is by head box and helmet keeping the head well forward of the spinal axis. In practice, imaging would be utilized to attempt to define accelerated or distorted degeneration in an already degenerating population. Controls in such a study would have to be both age, dimension, posture and degeneration matched.

The problem is compounded by the requirement to survey an asymptomatic population. The normal high proportion of degenerates in the adult population removes the mathematics of the situation from Bayesian realms, only for the target population (accelerated patterns and profiles of degeneration within that greater population) to return the problem to that of defining moving needles in moving haystacks. The risk/benefit analysis of such a program in a highly motivated and intelligent population is illustrated by the Bayesian consideration of one facet, the presence or absence of spondylolysis as a hazard to pars interarticularis stability under high +Gz. Given 1,000 pilots harboring a normal population of >5% defects with a test sensitivity and specificity both of 95% (outstanding and probably impractical in clinical radiology), the 905 test "normals" (N) would include 2 with defects whilst 47 of those 95 labeled "abnormal" (ABN) would in fact be normal and wrongly excluded from HPA flying if such a defect were an exclusion (Figure 4-1). Given a more likely 90% sensitivity and specificity, then 95 (68%), an actual majority of the 140 test "abnormals" would be falsely labeled normals and 5 (<0.6%) actual abnormals would escape detection (Figure 4-1). This "false abnormal" labeling would potentially exclude some of the best candidates if such a test was an ab initio criterion. It would create mayhem in an established pilot population. General, "blind" screening of a pilot or candidate population should be used with caution, defining the exact purpose of the examination, whether it is to protect or exclude those at risk and what will be the next step for those labeled "abnormal" when at least half will in fact be normal.

4.3 PROSPECTIVE TRIALS

Prospective trials are easier when breaking new ground in new populations and in new circumstances rather than re-examining established populations. In considering a prospective trial covering all HPA aircrew, the complexity of the task and the potential for misinterpretation of results merit consideration as well as the following:

1) The multiple significant factors involved include:

a) Posture, both habitual and imposed by the cockpit ergonomy, together with the potential for distortion of the overall results by the adoption of alternative postures during the course of the trial which could materially alter the prognosis for the individual. This would not be lost on aircrew at risk of being grounded.

b) Anthropometry and the differential effects of the variable relationships of standard cockpit dimensions and the wide variations in pilot physique.

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Figure 4-1: Imaging Used As A Test Rather Than As A Tool

Population: 1,000
Test: Sensitivity 90%
Specificity 90%
True Abnormals: 5%

		Real Anatomy N	Real Anatomy ABN	
		950	50	
Test Result	"N"	855	5	"Normal" 860 (5 real abnormals)
Test Result	"ABN"	95	45	"Abnormals" 140 (95 real normals)

Same
Sensitivity 95%
Specificity 95%

		Real Anatomy N	Real Anatomy ABN	
		950	50	
Test Result	"N"	903	2	"Normal" 905 (2 real abnormals)
Test Result	"ABN"	47	48	"Abnormals" 95 (47 real normals)

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c) Individual flying styles and techniques. Though "fly-by-wire" does impose a degree of standardization on individual flying style, successful fighter pilots have in the past included those who have exploited their individuality. High +Gz exposure is likely to be non-uniform, with individual profiles having a profound effect on spinal component mechanical creep, most obviously of the intervertebral disc.

d) While age has a univeral effect, the old adage that there are old and bold pilots, but no old, bold pilots has implications for the spine. Older pilots still flying HPA tend to look after themselves. But flying with one's head permanently "out" of the cockpit means that looking after oneself in dog-fighting terms may actually mean greater neck loading in the older pilot population than in their less confident or relaxed junior colleagues. Age has therefore many significant dimensions.

e) Anatomical predisposition due to: (1) congenital spinal and cranio-spinal anomalies; (2) acquired, often traumatic lesions, such as pars interarticularis defects which though absent at birth are present in >5% of the young adult population from which tomorrow's HPA aircrew will be selected; or (3) an acentuated disposition to spinal degeneration to which a family history may provide some clue.

2) Control Groups:

Controls would have to be selected to reflect at least the above variables, together with the accurate matching of significant changes in subject function and activity occurring during the course of such a trial.

3) Trial Inclusion Criteria:

Entry "normality" needs careful definition. Rejection of candidates on other grounds would already have produced a biased, skewed population. Should normality/abnormality be judged on past, family or social history; on symptoms or signs; on physical and intellectual performance; or by imaging?

4) Definition of Trial Outcome:

The criteria by which outcome would be defined would have to be agreed prior to trial initiation, together with the means of analysis. With the present pace of imaging development all present imaging criteria can be guaranteed to be archaic and probably discredited long before a study was concluded. If no effect of HSG operations were demonstrated, to what limits could confidence in such a result be held?

5) What then?

If no effect were detected while extending HSG operations to +12 Gz, would the trial then be repeated to +15 Gz? How much/long HSG would be necessary to exclude hazard? If abnormality were demonstrated, should asymptomatic pilots be allowed to continue flying? Should the symptomatic be rehabilitated or discharged? Leaving such questions to be answered in an ad hoc fashion as a trial developed, would ensure every effort by the subject population to skew the study to each individual's benefit.

4.4 IMAGING: GENERAL CONSIDERATIONS

4.4.1 Imaging System Performance

Problems of technique, system sensitivity (the ability to detect abnormality) and specificity (the ability to correctly label the individual as abnormal or normal) are compounded by the applicability of individual imaging modalities to particular problems. In clinical practice, this has led to a variety of techniques being developed to address particular problems. There is no one "universal" imaging method.

4.4.2 Standardization

1) Technique can be a problem. MR, magnetic resonance imaging, as a contemporary example, is a nightmare kaleidoscope of field strengths, sequence design, weighting and contrast techniques. Rapid developments and the likely introduction of electron as well as other nuclear (to date largely proton) resonance techniques ensure that the imaging methods of any prospective study will change beyond recognition during the course of that study.

2) Interpretation remains highly subjective while some techniques (such as ultrasound) are exquisitely operator dependent. Experience, anticipation, and team interaction all play their part. Indeed, they are the hallmarks of successful clinico-radiological collaboration. Yet such success in the service of the individual patient is anathema to the "unbiased" reporting required by a prospective trial. The fact that screening and the "correct" diagnosis of asymptomatic populations is unfamiliar to any established clinical radiological team adds a further degree of potential instability to the interpretation of pro-

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spective data.

4.4.3 Hazards

These fall into three main areas:

1) Physical. Deleterious effects of very high magnetic and rapidly switching radio-frequency fields have yet to be demonstrated. Conversely, the allergic hazards of contrast agents and the dangers of x-rays and ionizing radiation are constantly being reiterated.

2) Economic. The potential economic hazards to the individual, of loosing a career through the apparently random introduction of some new and potentially "unfair" process, are likely to exercise the minds and fears of most aircrews.

3) Emotional. To suggest that all are "degenerate" is likely to be less than acceptable to the rightly self-confident, -centered and -opinionated individuals who comprise a significant proportion of any successful HPA aircrew population. There is also the potential to set aircrew against their medical advisors and confidents, if there is a perception that doctor and pilot are pursuing different objectives. The former's primary interest then being held to be to prevent rather than promote the latter's determination to be the best and most effective man-machine combination since Creation.

4.4.4 Cost

Program cost has many dimensions:

1) The absolute cost of the imaging/review exercise or its contribution to the overall HPA operational budget, to which it would make a miniscule contribution. This can be quantified by an agreed program of imaging to be followed by all aircrew with a margin for the further imaging of symptomatic individuals. It would be complicated by the complexity of the imaging program required to address any/all potential conditions associated with or possibly exacerbated by HPA/HSG operations over the aircrew's lifespan. Financial cost will always remain a consideration with the costs of individual tests varying between countries. Generally if Sonography costs 1A, then conventional radiography costs 2A, CT 4A and MR 8-10A.

2) The cost/benefit relationship in a particular program. A massive amount of work could well be done only to be rendered absolete early on in any study.

3) The very considerable effort required to screen large numbers of asymptomatic aircrew and the clinical review of any actual or possible abnormal findings, together with the associated disruption to the individual asymptomatic pilots duties and routine.

4) Mistrust. The intensely practical nature of HPA operation could contrast with the often apparently haphazard requirement for the detailed clinical review and further imaging of aircrew who in their own and others' eyes were entirely normal. Maintaining trust in a study is time consuming and can strain clinical confidentiality.

5) The potential additional loss of valuable aircrew labelled abnormal, unless a prior guaranteed waiver was provided that the program itself would not ground those who still fulfilled present criteria. The study would be best introduced as part of the research, development and safety program associated with the introduction of a new aircraft type and the exploitation of new operational domains.

4.4.5 Imaging Availability

Intense competition and constantly improving imaging performance would require imaging to be undertaken at carefully selected and interlinked centres, backed with a central registry and a common data base subject to annual review by a practical yet specialist body such as AGARD/AMP.

4.5 CURRENT IMAGING METHODS

Appropriate imaging methods at present available include:

1) X-rays: Plain, stereo and tomographic.

2) Contrast studies such as discography and myelography.

3) CT, computer-assisted x-ray tomographic scanning, both standard and fine cut. Good bone definition, variable windowing and the availability of contrast agents mean that CT will continue to have a place in spinal and petrous bone imaging despite rapid developments in MR methodology.

4) Combined procedures, such as CAM, computer-assisted myelography (Myelography + CT).

5) MR, magnetic resonance imaging. To date this has been nuclear, usually proton (water) based, though electron resonance systems are on the threshold of clinical application and characterization. Variable magnetic field strengths, sequence design and a bewildering and expanding

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variety of techniques guarantees that whatever is selected as the basis for a prospective study today, will soon be rendered obsolete, whatever present intentions.

The two current areas of study are:

1. MR imaging:

a) Orthodox (and time-consuming).

b) Fast techniques that allow dynamic assessment and volume acquisition.

c) EchoPlanar, real-time imaging which displays actual flow and motion.

d) EchoVolumar, 3-dimensional imaging in which one dimension may be used to display chemical shift and provide both anatomical localization as well as biochemical characterization.

e) MR Microscopy provides in vivo histology, though at present it requires high strength magnetic fields which have yet to gain acceptance for human, clinical application and for which novel magnets will probably be required.

2. MR Spectroscopy, which will find an application in every tissue during the time scale of any prospective HSG study.

6. Ultrasound

Sonography and the exploitation of Doppler shift and colour coding not only allow real time and flow imaging and measurement, but are readily repeatable and without known hazard. It is however totally operator dependent both for anatomical demonstration and to a lesser extent for interpretation. It is best in soft tissues. Its penetration of mature bone is at present poor.

7. Isotope studies

These may be by simple isotope uptake scans (166, 203) or by more accurate techniques (such as SPECT, single photon emission computed tomography) required to display small areas of tissue disturbance (such as the pre-fracture cancellous bone failure which preceeds spondylolisthetic fracture of the pars interarticularis) (56, 92).

4.6 IMAGING EXPERIENCE

The persistence of so many different modalities is an indication not only of the rise of imaging costs, but also that each method has specific applications which remain best addressed by that method despite the rapid development of other technologies. In the surveillance of HSG aircrew, a choice has to be made either to select the most appropriate methods available today, accepting that they will soon be rendered obsolete and shortly thereafter difficult to obtain, or accept that surveillance will inevitably have to be conducted using a variety of rapidly developing and changing techniques. The latter in its turn would mean that clinical and anatomical criteria will continue to be paramount in aircrew surveillance. It will always be necessary to "treat the man not the scan". Clinical primacy avoids Bayesian problems by treating the individual as an individual rather than a unit in the system under review. On the other hand, this does mean that clinical history, examination and investigatory criteria will have to be regularised and coordinated through a central organization such as AGARD/AMP. Clinical assessment is beyond the remit of this chapter, but is central to the effective surveillance of the next generation of HPA aircrew who will exploit the abilities of the F-22/Eurofighter/Rafale/Gripen generation aircraft.

4.7 IMAGING TARGETS IN THE SPINE AND VESTIBULAR SYSTEMS

Selection of the appropriate imaging and modality depends on the target tissue or structure.

4.7.1 Spine

1) The general morphology of the spine as well as,

2) Spinal dynamics can be addressed both by plain films of the whole spine and its various parts in fully active flexion and extension and by MR which is particularly helpful in the sagittal plane and when extended up into the head to cover the posterior fossa and brain stem.

3) The intervertebral discs, their annuli, nuclei, the end plates and the characteristic changes in the adjacent vertebral bodies in disc degeneration (186) are best defined by MR.

4) Synovial facet and neuro-central joints are still best defined by CT as are osteo- and spondylophytes. That MR is often used is due to the ability of MR to image in any plain without the necessity for reconstruction in CT.

5) Ligaments (anterior and posterior longitudinal, ligaments flava, inter- and supra-spinus ligaments) though theoretically soft tissue and therefore ultrasound sensitive are in practice

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usually assessed during CT and MR review. The exceptions are prevertebral lesions (especially absesses and collections requiring needle biopsy) when ultrasound is invaluable.

6) Vertebrae: plain films and CT define most abnormalities and MR the rest (particularly at the Foramen magnum). The most difficult area to define is the pars interarticularis. Clinical suspicion is paramount (98) and oblique plain films the traditional method of choice and still the first step. CT is often disappointing (70) and MR surprisingly good at picking up the soft tissue in the bony discontinuity, if present. Symptoms of spondylolysis often preceed cortical fracture. In this situation, SPECT can define the cancellous failure of the pre-fracture stage (56).

7) Paraspinal muscle abnormalities can be displayed both by MR and by ultrasonography.

8) The spinal cord, subarachnoid space, meninges and the spinal canal contents together with the brain stem are best demonstrated by MR with Gadolinium DTPA or other contrast enhancement as indicated.

9) Spinal cord vasculature can be visualized by MR angiography and venography, with conventional angiography back-up as clinically indicated.

10) CSF circulation and cisterns, together with cord cavities, and

11) Dysraphic states are best defined by MR.

4.7.2 Vestibular

"Vestibular" imaging usually entails plain films to exclude obvious skull base destructive lesions; fine cut CT for temporal bone anatomy and MR for intra-petrous structures, the cerebellopontine angels, posterior fossa and brain stem.

4.8 IMAGING ORGANIZATION

Spinal and vestibular imaging is a tool, not a test. Just as tools are useless or worse if not properly utilized, so imaging has to be employed as a contributory part of a greater surveillance scheme. Imaging is commonly used in three circumstances:

1) as part of the admission gating criteria during ab initio selection. Imaging can be a useful adjunct if the admission criteria are clearly defined and agreed.

2) as part of the medical support of the service population, following standard clinical criteria.

3) as part of the protocol of a prospective trial. Here the major problem is that all humans are abnormal to a greater or lesser degree. Any such trial has therefore to have either defined tolerances of the degree of abnormality that is acceptable, or be designed to accept individuals as individuals, making their performance rather than their appearance the prime criterion.

4.8.1 Further Significant Considerations

Accepting this imaging organization is then faced by:

1) The Duty of Care. Both to the individual, the Service and the taxpayer. Clinically, the individual is paramount. The trust of aircrew and the usefulness of the attending physician depend on this.

a) The situation of aircrew has to be assessed in terms of possible culpable hazard to which they might be exposed both by the operational requirement and the investigation. Each will effect the other and define the risk/benefit equation for both the operation and the individual.

b) The need to establish clinically, backed by investigation where appropriate, whether or not an individual is at some particular, individual enhanced risk.

c) Prevention of hazard both by the exclusion of individual risk and by active counter-measures such as improved posture or reduced axial loading by the provision of light-weight helmets. Imaging can contribute to both individual assessment and the design of counter-measures (such as the dynamic MR imaging of head/neck posture and movement pattern imposed by seat and helmet configuration and design).

d) Therapy. An adequate history and examination of symptomatic aircrew may require further investigation. In spine and vestibular system, this usually by imaging.

2) The problems of ab initio screening: "selecting-out" individuals should be based on careful clinical assessment. It cannot be delegated to imaging used as a pass/fail test, if only for Bayesian reasons, let alone the likely blind selecting out of many of those who might otherwise be ideal candidates. Imaging is no substitute for formal individual risk assessment.

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3) The practicalities of surveillance and the screening of those already in the Service. The more rigorous the review, the more the abnormalities that will be revealed. This is particularly so if new modalities are introduced to examine the existing pilot population. Such "moving of the (investigatory) goalposts" should be used with caution. Altering medical standards can create not unreasonable dissatisfaction among the existing aircrew who have based their careers on one set of standards, only to find them being changed for technological rather than practical reasons. The introduction of new agile aircraft type does however provide potential grounds for "moving the goalposts" because the goalposts will of necessity change by virtue of the new domains the new type is being introduced to exploit. Similarly, the initially small numbers of pilots converting on to the F-22 and similar aircraft will allow detailed individual clinical review and the introduction of the recommendations of this report.

4) Imaging in prospective trials.

a) Large numbers of individuals and controls can be handled if the trial criteria are clinical, that is performance-based.

b) If, however, imaging were to be used as a pass/fail test (i.e., if anatomy rather than performance were the criterion), then the prevelenced of abnormality in any adult human population would mean that all the variables defined in the introduction above would have to be matched. Numbers would be restricted by the effort involved or only a sample of the whole population selected, a source of further error.

5) Data collection and retrieval.

Good imaging is expensive of money, time, expertise and above all, of enthusiasm. Good quality data are exquisitely dependent on the last. Clinical review and appropriate imaging of those converting to agile aircraft, rather than attempted ball-park surveillance of all HPA aircrew, are most likely to be useful, as well as discharging the duty of care to those exploiting the new operational opportunities (opportunities that are both for good and ill). At the same time, parallel clinical review of all symptomatic HPA aircrew with a common data base will ensure the maximum return on effort and expenditure, while targeting expensive imaging most effectively.

Practical Application

Utilization of the imaging discussed can be represented as a decision "tree" (Figure 4-2).

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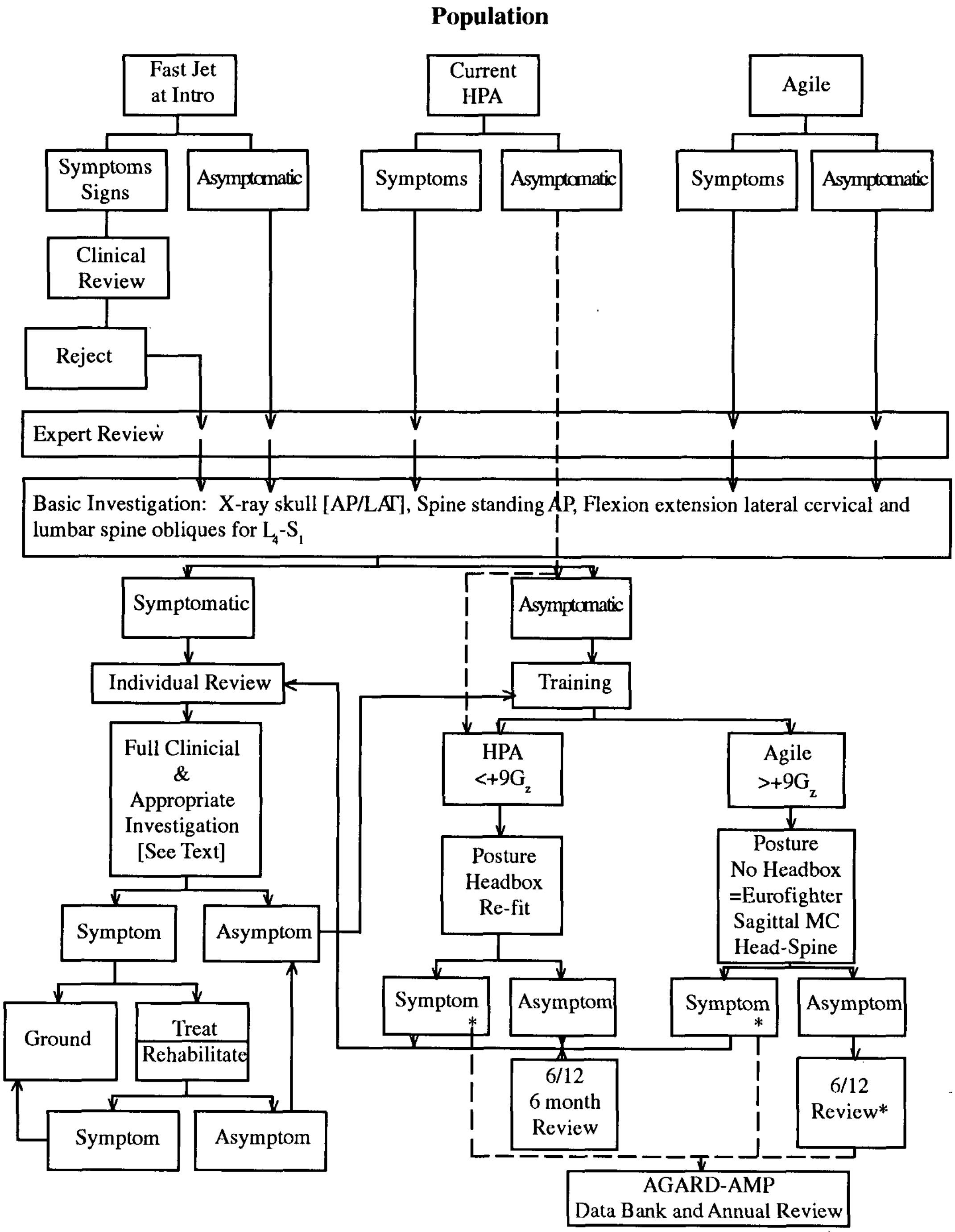
Figure 4-2: Diagnostic Pilot Selection Decision Tree



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CHAPTER 5

VESTIBULAR SYSTEM DYSFUNCTION FOLLOWING REPEATED EXPOSURE TO HIGH SUSTAINED G

5.1 NEURO-ANATOMY:

The vestibular system represents a complex neuro-anatomic interrelationship of neck, central nerous system, and inner ear structures. As well as the spine, four other anatomical areas are involved in AR317. <15+Gz operations have implications for brain stem, cervico-medullary junction and spinal cord as well as the peripheral vestibular system within the temporal bone. Whole brain motion; cerebral blood flow (CBF); the cerebral microcirculation; blood-brain barrier (BBB); brain ischaemic tolerance; the "G-free window" and second messenger effects are outwith WG17's terms of reference though they are central to hyper-G operation.

The basic arterial perfusion of spinal cord and brain stem depends on a major anterior axial arterial structure. This is represented by the anterior spinal and basilar arteries. Dynamically, these two structures (25, 26) are different. Below the C2 vertebral level, the spinal cord is longitudinally suspended within its pial envelope from the dura on either side by the dentate ligaments. Continuously and linearly attached to the spinal cord medially, the dentate ligament bridges the subarachnoid space, in an arch for each spinal segment and is attached focally to the dura laterally between each spinal nerve dural exit sheath. This arrangement, which is the bane of the spinal surgeon (as it limits the degree of spinal correction which this system of pial suspension will allow before pial corrugation, Virchow-Robin space distortion and chord venous outflow obstruction occur), provides axial stability for the cord despite the major cerebrospinal fluid (CSF) perturbations which occur within the spinal CSF subarachnoid cisterns with each heart beat, respiration, cough, head or neck movement, anti-G straining maneuver (AGSM) or change of Gz. Pure Gz related axial spinal cord disturbance at <15+Gz is less likely than spinal nerve root and dorsal root ganglion percussion or compression by anterior spinal column collapse in cervical kyphosis, or by gross cervical intervertebral foramen/exit canal pressure gradients in PPB.

The brain stem has no such stabilization or protection even though it has similar but even longer midline anterior perforators which extend back from the basilar artery to the IVth ventricular floor. Worse, its cross sectional area is larger and axially unstable which is not surprising as it was designed to lie horizontal under Gx. But under axial acceleration, this renders it susceptible to the axial sleeving phenomenon (116).

Unlike the dentate-stabilized cord and the sleeving stem, the cervico-medullary junction, between the brain stem medulla above and spinal cord at C2 (running through the Foramen magnum and the highly mobile cranio-cervical junction) is optimized for motion in and about all three spatial axes. Its blood supply is largely laterally derived (as the Lateral Medullary Syndrome demonstrates) and of a resilience which allows full head on-neck-movement without vascular compromise. Its smaller cross-sectional area appears to reduce its sleeving susceptibility. If lower medullary based, then Katchen's case (101) is the exception which proves this rule.

With few exceptions (46, 101, 147), the axial sleeving phenomenon has been the preserve of unlimited class aerobatic pilots practicing high -Gz sequences in turbulence and well outside competition meteorological limits. One unpublished episode (97) is anecdotally similar to Phillips' case (147) of cerebellar injury at 9 G but probably involved >11-Gz. High -Gz transients appear to be responsible for the civilian aerobatic cases, causing brain stem perforator-capillary bed disruption. Such insult is now familiar in restrained high speed vehicle occupant accident victims when peak deceleration occurs after head pitch forward has swung the brain stem into the main deceleration axis (18, 34, 67, 153). The typical lesions that result with flying are multiple, punctate brain stem hemorrhages. These can, and characteristically do, mimic vestibular disturbance by focal central vestibular connection interference.

The clinical hallmark is acute in-flight onset of vector related vertigo (VRV). In practice, care has therefore to be exercised to differentiate between central brain stem and peripheral vestibular acceleration-related lesions (50, 102, 173, 174). The latter have been found in animals subjected to extremely high levels of whole body acceleration (49, 85, 118, 142, 143, 205). Within our acceleration domain [<15+Gz] a minimum of +12G for >3 minutes has proved necessary to induce otolith separation (142, 143). An apparent intercept is provided by the observation by Davis (46) of benign paroxysmal positional vertigo that persisted for several months in a subject exposed to high levels of +Gz. But this could just as well be explained on a brain stem central basis as the reclining seat would have brought the brain stem into the main acceleration axis. If so, this

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may indicate another +Gz sector of the brain's acceleration toleration envelope.

5.2 HIGH Gz VESTIBULAR RELATED EXPERIENCE

This relevant information is provided by three populations exposed to G environments with magnitudes at levels considered conducive to vestibular damage: (1) Centrifuge; (2) High performance (largely fast jet) aircraft (HPA); and (3) Unlimited aerobatics.

5.2.1. Centrifuge:

The centrifuge experience in its turn comprises three separate domains (two human and one animal) though there may be intercepts.

1) Hyper-G, <15+Gz Johnsville pilot training for the X-15 program.

The persisting subjective problem from this unpublished experience was that of unremittent, if low grade clinical vestibular disturbance. This is in keeping with a chronic impairment of vestibular performance (57, 58, 174) and may indicate otoconial separation similar to that described by Parker et al (142, 143).

2) <9+Gz human centrifuge exposure.

This G exposure represents most of the centrifuge-riding population. With isolated exceptions (46, 52, 101), vestibular symptoms have been notable for their absence.

3) Animal ultracentrifugation.

Given that sufficient acceleration is applied for long enough, though the vectors have often been poorly controlled, otoconial detachment and sludging can be achieved (49, 85, 118, 142, 143, 205). As mentioned above, only the work of Parker et al (142, 143) is strictly applicable, but a minimum of 12G was maintained for 3 min 15 secs.

Though the case of Davis et al (46) may have been otoconial related, both her and Phillips' patient (147) recovered in the manner now familiar in brain stem injury and in high -Gz VRV which appears brain stem based and is discussed below. At least one Johnsville rider was left with a permanent deficit compatible with otoconial (17, 57, 75, 174) or utricular macular insult (37). It does seem that prolonged, constant vector <15+Gz can induce peripheral vestibular injury in man. However the vector and temporal dimensions of this inner ear acceleration failure boundary have yet to be defined.

5.2.2. High performance aircraft

Our experience here is all human and from three areas of aircraft performance:

1) Hypersonic flight.

Unplanned very high +/-Gxyz loading in the hyper-G domain [9-15Gz] where survival has occurred. However, the aircraft behavior was such that very rapid, out of balance, alternating autorotational states were the order and subsequent ejection added a further acceleration epoch. Immediate clinical concern was understandably for major systemic insult. The inconstancy despite the magnitude of the vectors experienced is probably the reason for the absence of persistent vestibular or recalled brainstem sleeving symptoms (212). The temporal requirement for the induction of tissue acceleration damage has been emphasised (183).

2) The "+9G Generation".

Initial experience with the F-15 and F-16 aircraft was relatively benign, in that only very brief excursions were made >8+Gz (66). Subsequent operational familiarity with and the opportunity routinely to utilize <9+Gz limited by reliable, pre-programmed fly-by-wire constraints have enabled "on the stops" flying without fear of overstressing the airframe. This in its turn produced a series of reports of spinal, principally cervical mischief in all those aircraft types so equipped [F-14, F-15, F-16, F-18] (4, 8, 13, 14, 21, 65, 109, 191, 192, 211). Needless to say rear-seat F-14 aircrew, with head and neck permanently twisted around the headbox to scan 6-o'clock in exactly those circumstances when unanticipated maximal onset rate to maximal programmed high +Gz is warranted, are among the worst effected. This USN/USAF experience has been confirmed by others operating agile aircraft (6, 76, 79, 80). The symptoms have been cervical with no "vestibular" effects.

3) The previous "6G" generation.

Though there were occasional direct (168, 169) and indirect (189) reports of cervical injury, careful review suggested that F4/MiG-21/Mirage aircrew pathology either reflected that of their general population cohorts (125) or was non-existent (124, 185). Occasional dramatic reports indicated operation well outside intended performance parameters (147). Sufficient experience was gained during this era to suggest that the next increase in manned aircraft performance would require attention to aircrew musculo-skeletal as well as car-

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dio-vascular factors (3, 32, 40, 44, 86, 95, 104, 127, 144, 152, 168). Though improvements in helmet design, construction and materials lightened neck axial loading, no attempt was made to improve pilot posture in general or neck biomechanics in particular by removing, replacing or re-positioning the ejection seat headbox, despite the limitation this structure imposed and continues to impose on rearward view in a new generation of aircraft dedicated to all-round vision. Again, persisting vestibular symptoms were lacking.

5.2.3. Unlimited Aerobatics.

This is a useful area of military study, not only because of the aerobatic lessons learned by the Red Air Force against the Luftwaffe in Spain and the Japanese Air Force in China during the 1930s, later applied to NATO Member States' discomfort, but because very high -/+Gz, well into the present area of interest has been used continuously and successfully at very low altitudes (>100 M, 328'agl) for many years with little obvious deleterious effect. Plus 12/-9Gz envelopes have been commonplace and practiced by international class (including World Champion) pilots well beyond commercial retirement age, yet alone the "fast-jet years". Age and the human frame alone are manifestly not contra-indications to these extreme Gz domains.

Differences from HPA operations include the great physical care such pilots take of themselves; their careful cockpit design and the fact that they operate within the "G-free window" of the human brain's ischaemic tolerance envelope, its 5 second ability to continue to function unperfused before the immediate and at high +Gz unheralded onset of coma. Seats are tailored to the individual. The pelvis is "screwed to the airframe" by a separate 3-point G-harness with the shoulder straps only tight enough to prevent upper body flailing in high-Gz autorotation. Though operating in supposedly friendly airspace, unobstructed vision and full head and neck maneuverability is mandatory to keep the (1 Km^3) competition box targets in sight at all times. Extended canopies and rear fuselage cut-outs avoid any airframe structural restriction of head position and movement. No more than minimal electrics and lightweight helmets, at best, are worn.

Progressively increasing exposure to high Gz over weeks is the norm. Once established, adaptation to high -Gz tolerance requires constant and continuous practice, exercise and stressing. After even short periods off flying, a return of the associated auto-regulatory adaptation especially to high -Gz, takes days to re-develop. Persisting vestibular symptoms are not a problem. Transient pilot-flight "high-G wobbles" are common in first exposure to violent maneuvers, but rarely last more than a few minutes.

Unlike Phillips' (147) case which was under high +Gz, the major problem in unlimited competition aerobatics has been exposure to high -Gz transients. The apparent cause is brain stem sleeving (116). Though one incident (97) at the Behkeschaba World Championships was anecdotally associated with a >-11Gz push-through (reproducing Phillips' clinical picture [147]), most cases have occurred at lower recorded -Gz levels (typically 7-8 -Gz) but invariably in turbulence or during over-rapid -Gz familiarization.

Clinical presentation is as an acute in-flight, usually single vector related vertigo. This continues once back on the ground. It settles slowly and spontaneously over the next 2-8 weeks. Clinical review and determined investigation to the limit of present scanning discrimination, reveal no more than occasional fine, irregularily scattered punctate brain stem lesions. Brain stem and somato-sensory evoked potentials, echo-cochleography, oto-acoustic emissions and full neurophysiological, -otological and -ophthalmological reviews are either normal, unhelpful or suggestive of minor, multifocal brainstem involvement as seen in demyelination but with relatively rapid and complete recovery. EEG and detailed psychometry have been unhelpful.

The syndrome is best managed clinically by recognition, definition, explanation, reassurance, good humor and time for spontaneous recovery. One individual had repeated symptoms during repeated returns to high -Gz aerobatic training. Though his clinical investigation was entirely and repeatedly normal, it was felt prudent to suggest alternative activities. Other pilots have experienced no further discomfort, distress or incident and have distinguished themselves in later World Championships.

The -Gz induced VRV syndrome indicates another portion of the human brain's acceleration tolerance envelope, albeit in an area little explored by the military since the 1940s. Phillips' pilot's full recovery (147) suggests the brain stem sleeving phenomenon can be reproduced under high +Gz, though just where this sector of the brain's failure envelope occurs remains to be determined. Personal experience of repeated short period air testing to +15Gz produced no more than transient subjective unease on returning to +1Gz. In contrast, the X-15 +Gz centrifuge profiles were prolonged. Nevertheless, the possibility of

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sleeving has to be considered when operating at <15+Gz. Pilots need to be aware of it and prepared to make an instrument return and approach to touch down without head movement. The likely persistence of symptoms after the aircraft has come to a halt suggests that assisted exit from the aircraft is prudent lest VRV inadvertently be elicited causing the pilot to fall and occasion further personal or airframe damage.

5.3 VESTIBULAR FUNCTION AND CLINICAL TESTING:

The peripheral vestibular system provides information related to one's orientation in space using information from five different sources located in small organs in each inner ear. Three of these organs sense angular acceleration in roughly orthogonal planes while the other two sense specific forces (linear acceleration and gravity). This peripheral information is integrated with that of other senses, including vision and proprioception from spinal and joint mechano-ceptors, to give information about the orientation of the individual in space and to allow for appropriate compensatory reflex responses. These reflexes adapt to enhance our ability to cope with changing gravitational and postural conditions. The three major reflexes involved are the vestibulo-ocular, the vestibulo-spinal, and the vestibulo-cervical reflexes. The first allows one to keep visual objects of interest stable on the retina while the others maintain head stability during body movement. Reflex movements so produced can be used to evaluate responses to vestibular stimuli. The classical description of the reflexes refer to canal functions.

In operational situations, it is unusual for acceleration conditions to occur in a simple form. One will never be exposed to an unvarying +Gz stress without even small linear accelerations in another direction, unless the subject is strapped in a rather unusual situation.

When considering the effect of sustained linear acceleration on the human body, and especially on the vestibular system, it can be expected that some modification develops in the human response to this type of acceleration. However, if modifications develop in the vestibular system, these may perhaps not remain restricted to the linear acceleration perception part, but also affect in one way or another the rotational acceleration perception component in this sytem.

Sustained microgravity is assumed because of altered otolith input to modify the postural control mechanism. Reschke et al (156) reported about a study in which they found significant deviations from results before and after space flight obtained from the Hoffmann reflex and the dynamic posture tests.

When microgravity will change the postural behavior, it is not unreasonable to expect also changes in this behavior following prolonged sustained acceleration with values exceeding 1G.

Testing of the vestibular function with basic, clinically oriented tests are time consuming. This hazard's acceptance by pilots and is further complicated by the multiplicity of available equipment and the sensitivity of test interpretation to individual expertise.

The adaptive, multisensory and integrative nature of the vestibular system makes it difficult for clinical tests either singularly or in batteries to detect the initially subtle, chronic modification of vestibular function likely to be induced by proposed levels of repeated exposure to HSG. The inability of clinical testing to detect abnormal vestibular function following spatial disorientation has been recently reconfirmed (167). Navy Aeromedical Research Laboratory (USA) (NAMRL) files of pilots suffering spatial disorientation were reviewed. Four were identified of which one would have failed the initial physical examination had appropriate clinical testing been undertaken. In the three others, one a survivor of a spatial disorientation incident, neurological examination and all subsequent routine investigations were within normal limits. However, when exposed to motion stimulation, all subjects exhibited abnormal perceptual responses when no visual references were available, with excessive and prolonged pitch and roll illusions. Prior to testing, the pilots had been able to suppress in-flight illusions by visual reference. Spatial disorientation then had occurred on limited panels such as when using night vision goggles in situations likely to promote spatial disorientation even in normal subjects. In these cases, it was only poor flight performance, repeated spatial disorientation or actual mishap which prompted investigation. Perceptual testing of spatial orientation has been pursued to "identify a class of pilots in whom pathological vestibular processes exist that predispose them to spatial disorientation; in effect, vestibular insufficiency. Similar excessive magnitude or duration of illusory perceptions have been related to motion sickness susceptibility. Enhanced, perceived pitch magnitude during centrifuge start-up and stop was noted in motion of susceptible individuals when compared to immune subjects (112) though Dobie, in a thousand case study had found no relationship between cupulography and air sickness susceptibility (51). More

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recently, a closer link has been demonstrated between perceptual anomalies and spatial disorientation (167).

The origin of such abnormal perceptual responses remains obscure. Are they "congenital", resulting from some genetic coding, acquired during the early stages of the spatial orientation system maturation or the result of late vestibular system pathology? If the latter, then chronic exposure to HSG might induce or enhance similar changes. Though there is no evidence in the literature, the possibility of chronic higher acceleration induced vestibular pathologies which might later impair pilots' performance does justify surveillance of those flying the next generation of high G, agile aircraft.

5.4 CLINICAL SURVEILLANCE OF HPA AIRCREW

The non-availability of normal comparative data and the absence of simple tests for vestibular function together with vestibular interaction with other sensory organs has resulted in the acceptance and training of pilot candidates who were later demonstrated to have harbored flight incompatible vestibular deficiencies (167).

Current clinical testing depends on the vestibular ocular reflexes. Separate dynamic eye movement tests are compared to doll's head eye movements. This assessment is relatively gross as such testing only interrogates the vestibular end organ indirectly. Vestibular mediated motor responses are next, but the vestibular contribution is directed by visual, somatosensory, auditory, and other afferent inputs. Such complications have led to batteries of tests, most notably the electronystagmography (ENG) test battery which has evolved over 40 years but still has deficiencies. The caloric test has the ability to stimulate one ear at a time using minimal equipment. However, test results of non-uniformity, the lack of a controlled stimulus, the necessity to infer vestibular pathology from indirect eye movement observation, the inability to stimulate more than one of the five vestibular components, and poor correlation with vestibular and oculomotor models lead to reliance on personal assessment rather than objective testing.

Prospective vestibular screening of individuals riding in centrifigues or flying HPA is unlikely to fare any better. On present evidence, a great deal of effort is unlikely to produce a useful result.

Nevertheless, efforts to devise effective vestibular screening programs have continued and been described in the report of the "working group on evaluation of tests for vestibular function" (197).

Tests were sequenced to minimize adaptation. The test battery was administered in the following order:

1) electronystagmography (ENG or electro-oculogram (EOG) calibration;

2) saccade test;

3) spontaneous nystagmus and gaze-evoked nystagmus test;

4) visual pursuit test;

5) positioning and positional test;

6) caloric test

Only qualitative data were obtained, the interpretation of which still required skill and experience. The six tests were lumped as "basic vestibular function battery category A".

Attempted quantitative testing involved calibrated recording of eye movements in response to visual stimuli: fast, slow and static positioning together with caloric stimulation. Equipment included: a reclining chair or examination table; recording electro-oculography (EOG); hot and cold calorics; prevention of visual fixation in a dark room by Frenzel's glasses (+20D) or dark goggles; and calibrated fixed and moving targets to test static gaze, fast (saccadic) and slow (pursuit) eye movements.

The following problems persist:

1) Lack of standardization between test laboratories, little agreement on the magnitude and duration of stimulation, and considerable variability in techniques.

2) DC-coupled EOG recordings are more accurate, yet many widely-used machines still employ AC-coupled recordings even though AC-coupling does not accurately record static eye position.

3) Eyes are frequently closed despite the associated inattention, eye elevation, reduced caloric response, and increased recording artifacts. The alternatives, a darkened room or light-tight goggles or lenses, remain to be standarized.

4) Open loop extended water irrigation is commonly used for caloric testing but with no uni-

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form, standardized temperature or duration. Most clinics tend to test with water temperatures of 30° and 44°C for 30 seconds.

5) The presence of nystagmus may be inferred from strip-chart records, scoring by hand methods, or displayed on-line by sophisticated computational programs. Standardized test criteria for recording and averaging data for the evaluation of ocular responses have yet to be agreed. After hand and doll's head eye movement testing, Hallpike and Dix vestibulo-cervical testing is the simplest. From the sitting position, the individual is laid down and the head immediately turned fully to either side and held there. Observed nystagmus and subjective vertigo is sought. Simple head rotation to left or right, then held there for one minute seems to give as much information. Head rotation has to be repeated to either side.

Vertigo and nystagmus provoked by this test are assumed to be generated from the cervical proprioceptive afferent system, even though marked head acceleration and rotation is involved. Not surprisingly, sensitivity is variable and specificity poor, resulting in many false positives and negatives. This order of performance would stultify any prospective study.

Nevertheless, as about 60% of all proprioceptive sensors in the human body are located in the neck, and the potential for cervical based vestibular and ENT symptoms described under Gz (135, 176), careful review (accepting the above reservations) of all HPA and agile aircrew developing vestibular systems is prudent. A central registry is indicated whilst at the same time work should continue to standardize vestibular testing and explore the perceptual dimension of orientation. As proposed by Rupert (167), this is the most promising route to quantitative and reproducible vestibular system testing.

5.5 ALTERNATIVES TO FORMAL VESTIBULAR TEST BATTERIES:

Spatial orientation as a means of vestibular testing, using motion devices and advanced disorientation trainers could be combined with the routine centrifuge training of agile and HPA aircrew. The latter is becoming common place throughout the NATO HPA community with disorientation trainers often integrated into centrifuge training facilities. Development of a standard vestibular test protocol to be incorporated into the disorientation training should be required together with a means of recording and reporting the results to a central NATO database for annual audit and review. Such testing would allow long-term prospective testing as well as picking up chronic deterioration in vestibular performance and allowing the documentation of acute vestibular complications in centrifuge training and HPA operations.

The feasibility of such a program should be pursued with Dr Rupert of NAMRL (U.S.) and a survey of centrifuge and disorientation training facilities undertaken. The difficulty of designing and validating a test protocol which could be pursued on each and everyone of the many and various motion devices available in NATO training centers should not be underestimated. But this is the most promising avenue to pursue as well as addressing the duty of care issues for the pilots of the next generation of HPA.

5.6 CONCLUSION:

There is little evidence to date of HPA/HSG related peripheral (end organ) vestibular damage. In anatomical, physiological and neuropathological terms, brain stem axial sleeving is likely to be the first central nervous system failure boundary to be encountered in the <15+Gz domain. Other areas of concern including enhancement of cerebellar ectopia [Chiari malformation] and cranio-cervical CSF circulatory disturbances, have not so far proved a problem. Simple routine vestibular surveillance through disorientation training, testing, and performance recording, incorporated into the disorientation training component of HPA operations is recommended.

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CHAPTER 6

CONSIDERATIONS FOR TOPICAL RESEARCH PROJECTS

6.1 INTRODUCTION

The requirement to conduct prospective research on the prevalence of spinal disorders in aircrew of fighter aircraft is difficult to determine. The high G environment that fighter pilots are exposed to potentially can cause permanent spinal disorders. Despite this, the evidence suggests that spinal injury is not common at high G; i.e., clinically reported injuries are few. If spinal injuries are occurring, they are: (a) not reported by pilots for fear of losing their flying status; or (b) subclinical process rarely manifested acutely, but delivering a cumulative insult, the results of which may become clinically evident in the fighter pilot population several decades from now.

Since the mid 1960's, offensive and defensive high performance jet aircraft tactics frequently subject pilots to high G levels. No prospective studies have been done to determine the long term effects of high G levels on the aviators in these aircraft. The skeletal system is especially important because of potential cumulative trauma effects. Some acute problems have been previously reported, but these have been limited to the cervical spine and, except where fractures were present, were self-limiting (sprains, strains, occasional temporary neurological deficit). (8, 101, 109, 168, 169, 191)

6.2 STUDIES INSPIRED BY THIS WORKING GROUP:

A study was carried out that searched USAF separation files in pilots. No significant differences were found between aerobatic and non-aerobatic pilots. A retrospective, cross-sectional study of twenty subjects who had ridden the centrifuge five to ten years ago and who had at least 100 centrifuge exposures was also conducted. Two control groups were used. The first consisted of twenty hypobaric research subjects while twenty airmen, matched for age, sex, and job specialty formed the second group. The small numbers involved allowed 100% of the questions (Appendix B) distributed to be returned. Centrifuge exposure was not predictive of back problems. The results of this study were presented to the 1993 Annual Aerospace Medical Association Meeting (195).

Another study surveyed the medical requirements (if any) for pilots to fly high performance aircraft. This survey was conducted in support of AGARD by the Armstrong Laboratory, Brooks Air Force Base, Texas (U.S.) and included aeromedical departments of 29 NATO nations that fly HPA. The questionnaire used for this study can be found at Appendix A. This survey has been completed with preliminary results reported at the 41st International Congress of Aviation and Space Medicine, 12-16 Sep 1993, Hamburg, Germany. Twenty of the 29 nations queried responded. Screening methods included history, physical examination and spinal x-ray. CT, MRI, or EMG were not used by any nation. Disqualifying defects were consistent among nations. Eighty percent of the countries considered musculoskeletal injury of HPA pilots as a serious problem. Although the effectiveness of screening methods were debatable, spinal screening was considered useful in selecting pilots of HPA (160). In addition to this study, a cross-sectional study of retiring and separating U.S. aircrew of all USAF aircraft is planned by the Armstrong Laboratory.

Other nations are also interested in the problem. A small longitudinal study of 30 F-16 pilots is being carried out by the Greek Air Force. The Belgian and Norwegian air forces are also screening their pilots and eliminating those considered unsuitable for HSG flight. They are also monitoring those pilots selected for HSG and will hopefully publish their experiences at sometime in the near future.

6.3 SPECIFIC CONSIDERATIONS FOR FUTURE STUDY DESIGN

6.3.1 Introduction:

AGARD Working Group 13 (similar in creation to this one) has been conducting a study of possible cardiovascular problems resulting from exposure to HSG. The recommendations made by that group (AGARD AR-297) led to an ongoing study. The experiences of those conducting that study are valuable to any group seeking to initiate an international collaborative research effort such as that discussed in this AR. Therefore, a meeting was held on 18 Dec 1991 at the Armstrong Laboratory with many of those persons involved in designing and conducting that study. A summarization of that meeting follows.

6.3.2 General Concerns:

The following general concerns were identified. When the study protocol is developed, there is a need to have a clear idea of what the study is trying to prove; i.e., how the data will be used. Problems may be encountered in (a) identifying the

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population at risk, and (b) relating specific injuries to flying HPA. A preliminary study of retrospective data may assist in designing the definitive prospective study. If a protocol is written with procedures set out too specifically, then problems may occur later if these procedures are unmakeable and need to be modified. Care must be taken in formatting historical data. Differences in nationalities can create problems; e.g., football in Europe is soccer in the U.S. and quite different from Canadian or American football. Be sure when designing a questionnaire to have a definitive standardized quantification measure for sports so that the level of activity can be accurately assessed.

6.3.3 Spine Study Concerns:

Selection of an appropriate control group is vital to the success of any study seeking to identify an effect of HSG on the spine. A good history from each subject is essential as one of the risk factors for spine problems is inheritance. Participating in sports activities may already have increased individual subject's risks, thus quantification of previous sports activities is extremely important. While an incidence study of neck problems is most urgent, the opportunity to collect data on the whole spine should not be ignored.

A well designed study will most likely include some sort of imaging. In light of the many problems of interpreting spinal images, a centralized diagnostic study should be considered to reduce variability in interpreting films. One copy of each film could be mailed to an independent diagnostic center.

As all adults older than 16 years have some degree of degenerative disease of the spine and have a high chance of past back injury, the question of selection of study subjects is extremely difficult. If the criteria for inclusion are too strict (e.g., no previous history of spinal disorders), then a large number of potential subjects could be eliminated, and the numbers necessary to identify significant differences between the control and study groups impossible to achieve. An important question is whether or not aircrew with a history of previous ejections or accidents should be included. The forces generated by catapult launches off naval aircraft carriers, and assisted landings are also a possible confounding factor. A count of the number of such landings and takeoffs could be useful.

The data collected should be analyzed to determine the variability of inter-individual controls. This information is necessary to determine the size of the subject and control groups. If variability is too high, then the large numbers of subjects required to identify significant differences between controls and subjects will preclude completion of the study.

As large number of subjects will need be surveyed, a successful study will most likely be a multi-service, international study. Continuous monitoring will be necessary to assure similar standards between diagnosticians of all participating countries. This is particularly important if MR is used as a diagnostic method.

The valuable information available from plain x-rays means that this method, regardless that newer imaging techniques are available, will likely be used in any definitive study. If x-rays are used for research purposes, rather than diagnosis and treatment, then the radiation hazard of x-rays necessitates obtaining informed consent from study participants. Although MR is much less hazardous, the interpretation of MR images is much more difficult.

Inevitably, any study that is conducted will identify pathology in the study participants. In common with any study of this type, the subsequent disposal of such participants creates a critical dilemma. If a pathology is identified that increases the subject's risk of injury due to HSG, then it is a duty of care of the physicians involved in the study to ground these individuals. However, if such a policy is adopted, then very few pilots will volunteer as they have concerns of being grounded. Under such circumstances, it would be difficult to obtain enough volunteers to conduct a successful study. The duty of care needs to lifted from the physicians running the study by a higher level policy decision, implied by protocol approval at a high level of military command.

6.3.4 Vestibular Study Concerns:

A vestibular study is considered more difficult to conduct than a spinal study. Acute injuries to the vestibular system either heal or are compensated for by the CNS making detections of previous injuries almost impossible. Where symptoms are manifest, it is often difficult to diagnose cause. Although a vestibular study would complicate a spinal study, the opportunity to investigate the vestibular system should not be lost if the effort is taken to organize a definitive spinal study.

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Some techniques that could be used for a vestibular study include:

1) Screening platform posturography with accompanying EMG measurements of forearm or calf muscles. This test quantifies data from the functional visual, vestibular and proprioceptive systems. The instrumentation needed is commercially available, computer driven, and simple to administer. This test could be used for both cross-sectional and longitudinal studies.

2) Evoked otoacoustic emissions and electrocochleography measure the micro-electrical milieu and would afford excellent tools for both cross-sectional and longitudinal studies attempting to identify a HSG effect on the cochlea.

3) Subjects riding centrifuges offer an accessible group already indoctrinated into the process of participating in a research program who could form the basis of a preliminary investigation. A previous ENG study (206) did show post G effects for up to 10 days.

As there has been little widespread awareness or practical experience of vestibular dysfunction among pilots as a group, they may be difficult to entice into a research program in the absence of a clear operational problem.

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APPENDIX A

SPINAL SCREENING OF NATO FIGHTER PILOTS: A COMPARISON BETWEEN THE MEDICAL REQUIREMENTS OF NATO NATIONS

BACKGROUND

The United States Air Force School of Aerospace Medicine in support of the Advisory Group for Aerospace Research & Development (AGARD) is conducting a study to help determine those fighter pilots who are at risk for developing spinal or back injury as a result of flying high performance aircraft. We are surveying the various countries that fly high performance aircraft to collect data on whether or not these countries screen their high performance pilot candidates for spinal abnormalities. The following questions will help us in our study:

QUESTIONS

1. What type of high performance fighter aircraft does your country fly?

___ F-14	___ F-5	___ Tornado
___ F-15	___ Mirage F-1	___ Mig-21
___ F-16	___ Mirage 5	___ Mig-29
___ F-18	___ Mirage 2000	___ Mig-31
___ F-4	___ Jaguar	___ Su-27

___ Other fighter aircraft (please list):

____

____

____

2. Do you screen the spinal column of your high performance pilot candidates with any of the following:

physical examination	____ Yes	____ No
radiographs (x-rays)	____ Yes	____ No
computer tomography (CT scan)	____ Yes	____ No
magnetic resonance imaging (MRI)	____ Yes	____ No
electrophysiology (EMG)	____ Yes	____ No

3. What back abnormalities are disqualifying for your high performance pilot candidates? Please list:

_____ arthritis of spine
_____ scoliosis: _____ degrees
_____ lordosis (symptomatic)
_____ kyphosis (symptomatic)
_____ spondylolisthesis (symptomatic)
_____ spondylolysis (symptomatic)
_____ herniated disc (HNP)
_____ fracture or dislocation of vertebrae
_____ spina bifida
_____ osteomyelitis of vertebrae
_____ recurrent disabling back pain
_____ fusion of two or more vertebrae
_____ other (please list):

____

____

____

____

____

____

4. Does your country consider spinal or back injury a problem in the pilots who fly the high performance aircraft? _____ Yes _____ No

Please explain:

____

____

____

____

____

5. If you screen your high performance pilot candidates with physical examinations, x-rays, CT scan, or MRI, do you feel this has decreased the incidence of spinal or back injury in your high performance aircraft pilots? _____Yes _____No

Please explain:

____

____

____

____

____

Thank you for your assistance. If you have any questions or if we can provide any further instructions, please contact:

Lt Col Herminio Cuervo, MD
Major Douglas Robb, DO
AL/AOCN
2507 Kennedy Circle
Brooks AFB TX 78235-5117 USA

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DEPARTMENT OF THE AIR FORCE
ARMSTRONG LABORATORY (AFMC)
BROOKS AIR FORCE BASE, TEXAS

4 Dec 92

AL/AOCN
2507 Kennedy Dr
Brooks AFB TX 78235-5117

Dear Colleague

At the Cljnical Sciences Division of the Armstrong Laboratory under the direction of Colonel James R. Hickman (MD), and in collaboration with AGARD, we are conducting a study into the effects of gravitational acceleration on the vertebral column of aviators.

As part of this project, we are conducting a survey of the various air forces who operate high performance combat jets. We are interested in obtaining informatión about selection criteria applied to the vertebral column of pilot candidates and the utilization of surveillance methods for high performance pilots.

The US Air Force does not employ selection criteria for the spinal column. We have developed the attached questionnaire to assist us in gathering data for this phase of the project.

Your assistance in the timely completion and mailing of this questionnaire will be greatly appreciated. We will happily share the results with the participants of the study, which will be submitted for publication.

Thank you very much for your kind help.

Sincerely

HERMINIO CUERVO, Lt Col, USAF, MC, SFS
Chief, Neurology Function

1 Atch
Questionnaire

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APPENDIX B

CROSS-SECTIONAL STUDY OF RETIRING/SEPARATING U.S AIRCREW FOR SPINAL DISORDERS

A cross-sectional study of retiring and separating aviators shall be done to determine the need for a twenty year follow-up study of aviation cadets.

A standardized questionnaire and physical examination will be administered to all retiring and separating aviators at the time of their exit physical examination. The total number of subjects in the survey will be determined. The physician administering the questionnaire will record any history of back or neck injury, sprains, strains, fractures, etc. The physical examination in asymptomatic subjects will consist of (as per Dr. Gonzales, Rehabilitation Center of South Texas): full range of motion of neck and lower back in all three planes measured with an inclinometer, straight leg raising, attention to posture (scoliosis, kyphosis, etc.) and an examination of the peripheral nervous system (as related to limbs). Those asymptomatic subjects who have abnormal physical findings on the screening examination will be referred to the Neurology Department of Wilford Hall USAF Medical Center for a final determination of disability (same as symptomatic subjects who meet a Physical Evaluation Board). Subjects with a history of non-aviation traumatic back injury (e.g.: motor vehicle accident, sports trauma, etc.) will be identified with the analysis. A questionnaire, similar to the physician administered questionnaire, will ask the examinee if the examining physician carried out the various required portions of the exit examination.

Individuals found to have spinal problems through the above mentioned evaluations and referred to Wilford Hall Medical Center for further study, will have at least the following included in their second phase evaluations: complete neurological evaluation, neck and lumbar range of motion three planes straight leg raising, MRI using the computerized "atlas" technology with volumetric reconstructions and intervertebral disc data. EMGs, nerve conduction studies, and circumferences of arms (if cervical) or legs (if lumbar). Other studies may be done as indicated.

All questionnaires, physical examination and special study results will be sent to the primary investigator at the Armstrong Laboratory, Brooks Air Force Base, for storage and analysis. We will analyze the results with a multiple logistic risk formula or a Cox proportional hazards model. The independent variables will be: actual flight hours in high performance aircraft, smoking history, height (stature), obesity index, age, family and personal history of back disability. The dependent variable will be compensation for spinal injury (neck or back) at separation/retirement.

There is no immediate risk to the participants since this is a questionnaire and physical examination survey. The results of either cannot harm the participants' military careers, since they will be in the process of exiting the military. Pilots applying for flying jobs with commercial carriers may be at risk if asymptomatic abnormalities are found.

There is no consent statement required for this project since there is no hazard to the participants. This is merely part of the routine separation/retirement physical examination which should be done anyway. The report shall include only summary statistics with no unique identifiers.

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APPENDIX C
AGARD SPINAL EXAMINATION WORK SHEET

All data must be entered as of the date of the spine examination
(CROSS-SECTIONAL STUDY ONLY)

A. SUBJECT GENERAL INFORMATION:

1. Subject Identification Number

_________/_________/__ __ __ __ __
country code alphanumeric 5 digit identifier

Country Codes:	01 Belgium	02 Canada	03 Denmark
04 France	05 FRG	06 Greece	07 Italy
08 Netherlands	09 Norway	10 Portugal	11 Spain
12 Turkey	13 UK	14 USA	15 Sweden
16 Other			

2. Date of Birth: ___/___/___ (mo/day/yr)

3. Height: ____cm Weight: ____ kg

4. Nationality of pilot: ____ (use country codes)

5. Country in which study was done: ____ (use country codes)

6. Sex: ____ M ____ F

7. Present Pilot Situation:

____ a. Pilot presently flying
____ b. Pilot not presently flying
____ c. Pilot leaving service

8. Flight Experience:

Aircraft # (*)	Dates Flown (month/year)	Approx Total (flight hours)

(*) See Appendix C-A

B. SUBJECT SPINAL HISTORY:

1. Pilot has had clinically diagnosed spinal problems:
____ Yes (explain) ____ No

2. Clinical diagnoses (dates)

3. X-rays/MRI taken? (dates/location):

____ a. Conjunction with suspected spinal problems (if yes, explain):

____ b. Not in conjunction with suspected spinal problems

____ c. Diagnosis (dates)

4. Aircraft Ejection Injury History

a. Spinal X-rays taken? ____Yes (explain) ____ No

Date _______ Location (Clinic/hospital address)_______________

b. Boney Spinal Involvement ____Yes (explain) ____ No

Fracture/Compression_______________
Vertebra location(s)_______________

c. Interrupted Flying? ____ Yes (explain) ____ No

Duration grounded (days) _______
Date returned to flying _________

C. EXERCISE AND PHYSICAL HISTORY:

1. See attached Exercise Questionnaire (Appendix C-B)

2. Sport/Physical Injury ____ Yes (explain) ____ No

a. Involve Boney Spine ____ Yes (explain) ____ No

Fracture/Compression_______________
Vertebra number/location_______________

b. Spinal X-rays taken?____ Yes (explain) ____ No

Date _______ Location (Clinic/hospital address)_______________

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APPENDIX C-A LIST OF NATO AIRCRAFT

1. Temoin - Non pilot
2. A 3
3. A 4
4. A 5
5. A 6
6. A 7
7. A 10
8. Alize
9. Alpha Jet
10. AMX
11. Andover
12. AT 37
13. Avio Jet
14. Atlantic
15. Azor
16. B 1
17. B 52
18. B 57-66
19. B 707 - C 135, 137 E3
20. B 727 - C 22
21. B 737 - T 43
22. B 747 - E 4
23. BA 146
24. BAC 111
25. Belfast
26. Buccaneer
27. Buffalo
28. C 1 - Tracker
29. C 5
30. C 9 - DC 9
31. C 47, 117 - Dakota
32. C 101
33. C 118 - DC 6 - DC 7
34. C 119
35. C 123
36. C 124
37. C 140 - Jet Star
38. C 141
39. C 212
40. Cambera
41. Challenger
42. Caribou
43. CF 100
44. CL 215
45. CP 107
46. CT 39 - C 20 - C 21
47. DC 8
48. Devon Sea
49. Draken
50. E 3 - Hawkeye
51. Etendard 4
52. F 4 Phantom
53. F 5 Tiger T 38
54. F 8 Crusader
55. F 14
56. F 15
57. F 16
58. F 18
59. F 84
60. F 86
61. F 100
62. F 101
63. F 102
64. F 104
65. F 105
66. F 106
67. F 111
68. Falcon 10, 20, 50, 900
69. Fouga
70. Fouga Magister
71. G 91
72. G 222
73. Gnat
74. Harrier-Sea
75. Hawk
76. Hercules C 130
77. HS 125
78. Hunter
79. Jaguar
80. KC 97
81. Lightning
82. MB 326
83. MB 339
84. Mirage 2000
85. Mirage 3
86. Mirage 4
87. Mirage 5
88. Mirage F1
89. MS 760
90. Mystere 4
91. N 2501
92. N 262
93. Nimrod
94. P 3 - Orion
95. P 166
96. PD 808
97. Pembroque
98. S 3 - Viking - C2A
99. S 211
100. SMB 2
101. Super Etendard
102. T 33
103. Tornado
104. Transall - C 160
105. Tutor
106. VC 10
107. Venom
108. Vulcan
109. Helicopteres
110. Other light a/c
111. Other transport a/c

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APPENDIX C-B

EXERCISE QUESTIONNAIRE (page 1 of 2)

Identification number: ______________

Country Code: ____________

Birthdate: ___/___/___

ACTIVITY	# hrs per day	3 days per week	Dates (mo/year) Began	Ended
Aerobics				
Archery				
Badminton				
Basketball				
Bowling				
Boxing : in ring				
Boxing : sparring				
Canoeing : competition				
Canoeing : leisure				
Circuit-training				
Climbing hills : with 20 kg				
Climbing hills : with 10 kg				
Climbing hills : with 5 kg				
Climbing hills : with no load				
Cricket : batting				
Cricket : bowling				
Croquet				
Cycling : competition				
Cycling : leisure 15 km:h				
Cycling : leisure 8 km:h				
Field hockey				
American football				
Golf				
Gymnastic				
Horse : race, gallop				
Horse : training				
Horse : walk				
Horse : trot				
Ice hockey				
Judo				
Marching, rapid				
Masculation : circuit (Men)				
Masculation : circuit (Women)				

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EXERCISE QUESTIONNAIRE (page 2 of 2)

Identification number: ______________

Country Code: ____________

Birthdate: ___/___/___

ACTIVITY	# hrs per day	3 days per week	Dates (mo/year) Began	Ended
Running, cross country				
Running, level, 5'30 per mile				
Running, level, 6' per mile				
Running, level, 7' per mile				
Running, level, 8' per mile				
Running, level, 9' per mile				
Running, level, 11'30 per mile				
Scuba diving, moderately active				
Scuba diving, very active				
Skiing-hard snow/on hill/max speed				
Skiing-hard snow/on flat/walking				
Skiing-on flat/moderate speed				
Skiing-powdered snow/leisure (Men)				
Skiing-powdered snow/leisure (Wom)				
Snow shoeing, powdered snow				
Soccer, European football				
Squash				
Swimming : breast stroke				
Swimming : crawl, leisure				
Swimming : crawl, fast				
Swimming : backstroke				
Swimming : sidestroke				
Swimming : treading, normal				
Swimming : treading, fast				
Table tennis				
Tennis				
Volleyball				
Walking : plowed field				
Walking : fields & hillsides				
Walking : asphalt road				
Walking : grass track				
Weight training				

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CHAPTER 7

RECOMMENDATIONS

7.1 INTRODUCTION:

Since this review is concerned with long-term effects of sustained G on two entirely different anatomical/physiologic systems; i.e., musculoskeletal (primarily the spine) and vestibular (principally the otoliths), each will be considered separately regarding recommendations for: (a) the need for specific actions and, if needed; (b) what those actions should require.

7.2 SPINAL SYSTEM:

Working Group 17 was formed to write this AR 317 with directions to focus primarily on the long-term effects of HSG. In spite of the fact that information is not available that establishes causal relationship between long term effects of the spine and HSG, we recommend several courses of action that still seem prudent. Also, it became apparent that acute symptoms of spinal injury commonly occur in HPA pilots. Indeed, considering the propensity of evidence of acute neck injury and its significant effect on operations, this chapter includes recommendations for dealing with both chronic and acute spinal problems.

7.2.1 Spine Study Requirements:

Primary concerns involve the collection of additional data regarding spine degenerative changes as they relate to repeated HSG exposure. Prompting the direction is that the information on this subject is contradictory involving small subject numbers; i.e., an epidemic of significant spinal diseases in fighter pilots does not at present exist. It is clear, therefore, if HSG does cause spinal diseases, the incidence is not very high. Yet, future HPA that are capable of higher levels of sustained G, would benefit from detecting low-level of occurrence, thereby, providing some warning of future problems. Also, there is always considerable interest within the acceleration scientist population to explore the possibilities of increasing our knowledge base in HSG.

There are two basic approaches to obtaining more data specific to HSG: (a) active or (b) passive. The former involves developing experimental protocols to study pilots' spines of HPA either in a longitudinal study or cross-sectional study. The latter approach involves collecting information from uncontrolled sources such as: (a) pilots of HPA reporting back injuries; (b) flight surgeons "studying" pilots; and (c) post mortem data from aircraft accident victims. Relating those data to documented HSG duration data from the same pilots would increase the value of this type of study.

Although the active approach would provide the best information, the high cost, logistical problems, and time requirements make it less acceptable. Collecting more passive data with greater specificity towards spine problems is recommended by this working group. A typical approach that uses this discipline is detailed spine-neurological examinations of aircrew of HPA upon their discharge or retirement from the Air Force as proposed for the U.S. Air Force by the Armstrong Laboratory (see Chapter 6).

7.2.2 Aircrew Selection:

The genetic code of all individuals embodies information useful in predicting to some extent spinal health and disease. Familial history would be considered in some detail in selecting aircrew for HPA. In addition, complete medical physical examinations focused on the spine that include x-rays and a complete spinal functional assessment (quantification) that is yet to be developed (see research requirements section that follows).

Caution must be exercised here because there is much more to flying HPA than a healthy spine; i.e., intelligence, dexterity, orientation sense, excellent situational awareness, are just some of the many needed attributes of a fighter pilot.

7.2.3 Aircrew Training:

Once selection has provided the best that the population has to offer, training directed towards spinal health is highly recommended. Training and education always offer great benefits at low cost. Training should involve: (a) physical condition, (b) proper posture; and (c) mobility under G.

Physical training regimens for improving G-duration tolerance have been developed and are either highly encouraged on a voluntary basis for aircrew or required by regulations (see AGARD-AG-322). A subset of this training regimen is neck exercises. These should be elevated in importance and require neck strength testing for compliance. Total spine exercises (particularly the lumbar region) should be developed and made an essential (required) part of the aircrew of HPA physical conditioning program.

Physical training therapy rooms with skilled trainers and/or therapists to manipulate the

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spine, etc. following HSG exposure should be provided for every appropriate squadron -- located next to the aircrew weight-training room. These would be made available for aircrew immediately following each day's sorties involving HSG.

Proper body posture with emphasis on lordosis would provide considerable benefits for maintaining a healthly spine at 1 G and during HSG. Training for lordosis should be instituted at the beginning of flight training.

Learning proper physical mobility regimens including head movements during exposure to HSG requires training in a high G environment. Centrifuges are expensive to operate and present coriolis problems with head movement. Aerobatic aircraft are cheap to buy and operate (compared with high performance jet aircraft) and provide the rapidly changing G environment to train proper mobility under G as well as fighter maneuvering techniques and skills. They also are an economical means of maintaining G-conditioning.

7.2.4 Aircrew Education:

Pilots should have practical knowledge about the structure of the spine and how it functions at both 1 G and during HSG (see "Research" that follows in this section). Their information is also important in directing their attention and instilling motivation in performing the proper exercise regimens for the back on a regular basis. Educate aircrew about proper body posture emphasizing the importance of lordosis (see Aircrew Training above).

Neck injury potential under G should be stressed and the problems of head movement in the HSG environment (to check six) defined.

7.2.5 Equipment Modification and Development:

Present ejection seat headbox design compromises spinal performance. Improved designs should be developed and incorporated in newly built and in refitted aircraft routinely during upgrades.

Light-weight helmets should be provided for HPA aircrew. Present progress in reducing helmet weight should be continued. Head-mounted equipment should be designed for minimum weight, moved elsewhere if possible, and be positioned and integrated on the head providing the optimum center of gravity.

Development of neck support equipment that becomes functional (deployed) during the onset of G, and not obtrusive to pilot performance, should be initiated. Headbox contouring to provide a high G park position in full head-neck extension may be a useful option.

7.2.6 Research Requirements:

Research should be initiated and supported with adequate resources by all NATO countries emphasizing the following areas in support of a healthy spine during HSG. Specific suggested topics follow:

1) Improved knowledge about head-neck motion/function under HSG.

2) Research and development of improved reliable techniques to properly assess spine function; i.e., the neck and lumbar areas primarily.

3) Development of optimum spine strengthening exercise program for pilots that are effective, but require little time to perform (time effective exercises).

7.2.7 Conclusion:

To conclude, countries that are now performing active data gathering studies on spinal injury of HPA aircrew on their own initiative should be encouraged by AGARD to continue. The Biodynamic Committee of AGARD/AMP should provide a forum for a "technology watch" on this topic, requesting annual reports on the progress of these studies. A follow-on AGARD symposium on this topic should be planned before the turn of the century to monitor and encourage progress in this important area of aircrew protection from G hazards.

7.3 VESTIBULAR SYSTEM:

Testing of vestibular function with basic test batteries are time consuming procedures. They can raise acceptance problems from pilots and from management because of unpleasant side effects.

The adaptive nature of the vestibular system means that a basic test battery would not provide enough information to detect persistent alterations of the function induced by repeated exposure to HSG. Such inadequacy of clinical testing alone to detect abnormalities of the vestibular function related to spatial disorientation has been shown recently (167). Bearing this in mind, it may be of interest to introduce testing to address the "perceptual" side of the spatial orientation system, in order to assess global function rather than only limited responses at the vestibular level. As an example, the Pensacola Vestibular

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Test Battery (PVTB) developed at NAMRL could answer this question and potentially increase the probability of detecting vestibular long term effects of HSG.

From a practical point of view, the PVTB in itself does not directly alleviate the concerns raised about duration and acceptance of the testing. However, spatial orientation tests could be easily combined with centrifuge training. Centrifuge training is now widespread in NATO nations for pilots flying high performance fighter aircraft and in most cases, disorientation trainers are located near centrifuge facilities.

A vestibular testing protocol designed to address chronical G-effects could and should be conducted prior to any centrifuge training session. Such testing would allow not only a long term vestibular follow-up of pilots exposed to HSG, but also assessment of acute vestibular risk of centrifuge training.

7.3.1 Recommendations are:

1) To review the availability, characteristics and performances of disorientation trainers located close to centrifuge training facilities.

2) To evaluate and advise about proper vestibular test procedures in centrifuge training programs, to be conducted within a reasonable time limit.

3) To design standard test procedures accommodating characteristics and performances of the various disorientation trainers.

4) To consider the introduction of unlimited aerobatic aircraft early in training using the whole flight envelope.

5) To develop a NATO database of both spinal and vestibular problems in all aircrew.

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Neck injury	Biomechanics of spine	

14. Abstract

Medical concerns of mechanical loading of biological systems during repeated sustained acceleration exposure of high performance aircraft were expressed during an AGARD conference of 24th–28th April 1989 (AGARD-CP-471) entitled "Neck Injury in Advanced Military Aircraft Environments". Biological systems of primary concern were direct effects on the spine causing neurologic injury and on the otoliths of the vestibular system causing disorientation related pathologies. In addition, secondary vestibular effects can occur from cervical pathologies. The technical evaluation and overview of that conference expressed concerns that "large gaps exist in our clinical and biomechanical knowledge of the problems of neck injury in high performance aircraft. Advisory Report (AR) 317 addresses those concerns with an in-depth review of available pertinent information with recommendations on several courses of action directed towards the spine and vestibular systems.

Specific topics covered include:

(a) the physical environment of aerial combat maneuvers;
(b) anatomy and biomechanics of the spine;
(c) G-loading effects on the musculoskeletal system of the spine including risk factors and the prevention of injuries;
(d) imaging considerations;
(e) high sustained G effects on the vestibular system and methods to test organ dysfunctions; and
(f) topical research proposals.

Recommendations include:

(a) study requirements;
(b) aircrew selection training and education;
(c) equipment modifications and development; and
(d) research requirements.

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