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U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject: INJURY CRITERIA FOR HUMAN EXPOSURE TO IMPACT

Date: 6/20/85
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Change:

1. PURPOSE. This advisory circular describes a range of impact trauma which may be used to establish bases for acceptance levels or performance criteria in the evaluation of occupant survivability characteristics in civil aircraft.

2. RELATED FEDERAL AVIATION REGULATIONS (FAR) SECTIONS. Sections 23.561, 23.785, 25.561, 25.563, 25.785, 25.801, 25.803, 27.561, 27.785, 27.801, 29.561, 29.563, 29.785, 29.801, and 29.803.

3. RELATED READING MATERIAL.

a. Aircraft Crash Survival Design Guide; (Volumes I-V); Simula, Inc.; USARTL-TR-79-22(A-E); 1980; Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia 23604.

b. Bioastronautics Data Book; NASA SP-3006; 1973; National Aeronautics and Space Administration (NASA), Washington, D.C. 20546.

c. Human Tolerance to Impact Conditions as Related to Motor Vehicle Design; SAE J885; April 1980; Society of Automotive Engineers (SAE), Warrendale, Pennsylvania 15096.

d. Whole Body Tolerance to Impact with Lap Belt-Only Restraint; Laananen, D.H; TI-83405; May 1983; Simula, Inc., Tempe, Arizona 85282.

e. Human Exposure to Impact with Two Point (Lapbelt) and Three Point (Lapbelt and Diagonal Shoulder Belt) Restraint Systems; Chandler, R.F.; Gowdy, R.V.; Memorandum No. AAC-119-83-7; August 31, 1983; Protection and Survival Laboratory, Civil Aeromedical Institute, Mike Monroney Aeronautical Center, Federal Aviation Administration, Oklahoma City, Oklahoma 73125.

f. Human Survival in Aircraft Emergencies; Yost, C.A.; Oates, R.W.; January 1969; National Aeronautics and Space Administration, Washington, D.C. 20546.

g. Proceedings of the Stapp Car Crash Conference; (published annually since 1966 by the SAE under various SP numbers); Society of Automotive Engineers, Warrendale, Pennsylvania 15096.

h. Impulse Analysis of Airplane Crash Data with Consideration Given to Human Tolerance; Huey D. Carden (NASA Langley); SAE 830748; April 1983; Society of Automotive Engineers, Warrendale, Pennsylvania 15096.

Note: Initial inquiries for any reading material in this paragraph may be directed to the address in the applicable subparagraph.

4. BACKGROUND. The scientific study of human exposure to impact began during World War II when ejection seats were developed for high-speed aircraft. The work of Geertz and Ruff in Germany developed basic criteria which are still in use today for evaluating seat and restraint performance. After the war, the work was expanded by Stapp and other scientists working primarily for the U.S.A. military services. Eiband provided a concise summary of this early work. The concern for automobile crash safety which developed during the 1950's and 1960's resulted in a great expansion of studies to increase impact injury protection offered to a civil population. Guidelines for the application of these studies' findings to Army helicopters is found in the Aircraft Crash Survival Design Guide; and for automobiles, in various Society of Automotive Engineers documents and in the Federal Motor Vehicle Safety Standards. The developments can also be followed in the Proceedings of the Stapp Car Crash Conferences, published annually by the Society of Automotive Engineers since 1966.

5. DEFINITIONS.

a. Human Tolerance. Whole body human tolerance limits result from tests with voluntary human subjects who are exposed to increasingly severe impacts while being held by a specific seat and restraint system. The level of the impacts is increased until a subject feels that further tests would be unacceptable. Injury is seldom the endpoint for such tests, but when injury occurs it is often accidental and has always been minor in nature. Tolerance limits from such testing have limited general application for systems intended to protect humans against serious injury or death for they represent a voluntarily accepted impact level and not an impact level representative of serious injury or death.

b. Injury Criteria. Injury criteria describe the trauma limits of individual human body components. These are more generally applicable to a variety of impact injury protection system designs. To provide data for protection against serious injury or death, biological surrogates are used instead of human subjects in tests; however, correlation of data between the biological surrogates and living humans is difficult. Moreover, for evaluating the performance of a protection system, an anthropomorphic test device (ATD) may be used instead of a biological surrogate, and the ATD is only a rudimentary representation of the human body. Impact injury criteria should be expressed in parameters which can be measured on an ATD.

c. Anthropomorphic Test Device (ATD). An ATD is a dummy used in place of a human for evaluation of impact injury protection systems. While many dummy types have been manufactured, the only standardized adult size ATD generally available in the U.S.A. is the one described by 49 CFR 572. This device, commonly called the Part 572 dummy, provides only approximate correlations with humans, and considerable resources are being expended to develop better ATD's. Impact injury criteria determined using biological surrogates should be expressed in parameters which can be measured on an ATD.

6. DISCUSSION.

a. Goals.

(1) The goal of this advisory circular is to provide guidance regarding useful human impact injury data which may be used to establish bases for acceptance levels or performance criteria in the evaluation of occupant survivability characteristics in civil aircraft. The human impact injury data provided herein are neither design criteria nor design goals, for it should be accepted that impact injury protection is a systems consideration with the human occupant as only one element in the system. Aircraft designs that absorb impact energy, help control the impact environment, maintain adequate living space, provide egress pathways for rapid evacuation, and use fire resistant systems to provide adequate time for egress, contribute much to occupant survivability. The occupant protection system elements (such as occupant/seat restraints, equipment, and furnishings) which are closest to an occupant, play a major role in injury protection. It is the proper interaction of all these and related elements which should be addressed to provide improvement in occupant protection against injury.

(2) The goal of any impact injury protection system should be to reduce the level of injury insofar as possible; from fatal to nonlife threatening, to serious, to minor, to none. The extent to which progress can be made along that chain depends on many factors:

(i) Personal characteristics (age, sex, physical condition) of the occupant influence the ability to withstand the force of impact;

(ii) Restraint system design details govern the placement of loads on the body at locations and at levels where loads can be most readily taken;

(iii) Orientation of the impact vector relative to the occupant governs which components of the body are most highly stressed;

(iv) A seat, which can provide distribution of load over the body and absorption of energy, may reduce the stress in the body;

(v) If the occupant/seat restraint does not preclude secondary impact of an occupant with the interior of a passenger compartment, then the ability of the cabin interior to distribute the impact load over the body segments and absorb energy influences the stress in the body from secondary impact; and

(vi) Finally, the characteristics of the impact pulse, such as impact velocity and the "shape" of the time history of the acceleration (including duration, maximum levels, effective onset rate, etc.), influence the stress in the body.

b. Whole Body Impact Tolerance.

(1) Considering the many factors influencing the ability of a system to protect against impact injury, any simple statement of tolerance should be heavily conditioned. Eiband, in 1959, attempted to compile a summary of the knowledge existing at that time relative to human tolerance to impact and attempted to present it in a simple form. He chose to represent each test result as a point on a log-log plot of acceleration vs. duration. The value of acceleration (or deceleration) chosen for this point was the maximum acceleration measured in the test, and the duration was the duration of that maximum acceleration. This approach was effective at that time because most of the test data was obtained for ejection seat tests, where the acceleration pulse was roughly trapezoidal in shape, and could be fairly represented by duration and magnitude of the maximum acceleration; however, if the pulse shape deviates significantly from a trapezoidal or square shape, this method becomes ineffective. For example, the triangular pulse shape often recommended as representative of aircraft crash deceleration would not even appear on a log-log plot since the peak deceleration has no duration. Also, a deceleration pulse with a superimposed short duration spike would be characterized by the amplitude and duration of the peak acceleration of the spike, and all other characteristics, such as velocity change or energy, would be ignored. Indeed, such a pulse would appear to be no different than a pulse composed only of the spike.

(2) This advisory circular will retain the log-log format, but will interpret the data according to a method recently used by the Army in evaluating energy absorbing seat performance. This method measures, and plots, the duration of all acceleration levels which appear in the acceleration pulse of the test. Thus the test is represented as a curve, rather than just a single point on the log-log plot. A series of tests will appear as a family of curves, and the tangent to those curves represents an envelope of the maximum acceleration and duration of maximum acceleration to which a human was exposed in the test series. While this provides a more universal means of including a variety of pulse shapes, it cannot consider all of the factors previously mentioned. Also, since it retains the log-log tolerance format originally proposed by Eiband, it suffers from the same possible misinterpretation that any test or crash, which can be plotted within the tolerance curve, is tolerable without regard to velocity change.

(3) The voluntary exposure areas of Figures 1 through 4 represent the acceleration levels and durations which have been tolerated by volunteer human subjects using the restraint concept indicated. The areas titled "low probability of life threatening injury" in Figures 2 and 4 represent accidental exposure of humans which resulted in reversible injuries.

c. Impact Injury Criteria. Of more importance for evaluating the performance of impact injury protection systems are measurements which can be made during testing. Historically, measurements of acceleration have been used as impact injury criteria, but these measurements have only been made popular by the ready availability of accelerometers rather than the significance

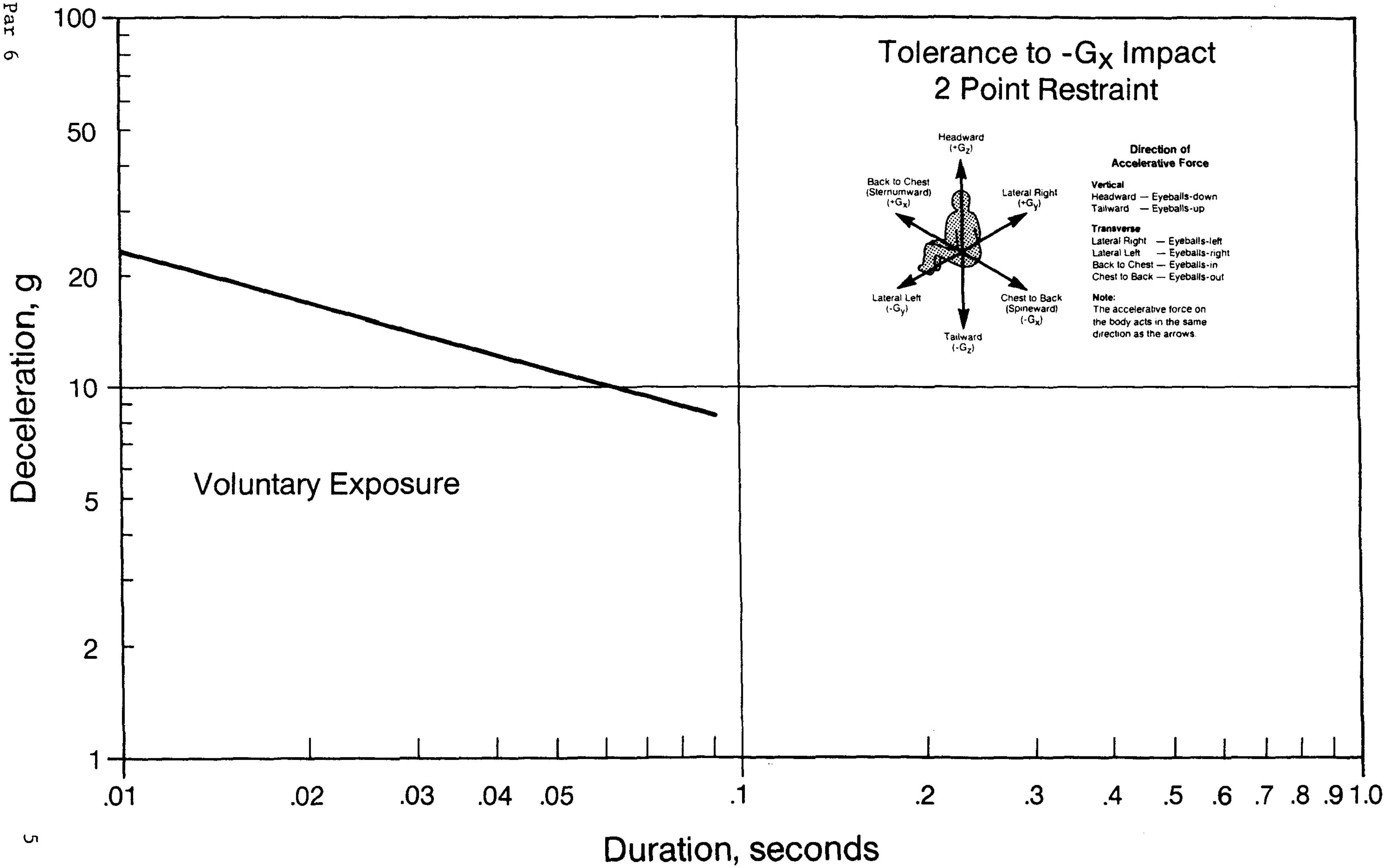
Tolerance to $-G_X$ Impact
2 Point Restraint
Headward
($+G_z$)
Back to Chest
(Sternumward)
($+G_x$)
Lateral Right
($+G_y$)
Lateral Left
($-G_y$)
Chest to Back
(Spineward)
($-G_x$)
Tailward
($-G_z$)
Direction of Accelerative Force
Vertical
Headward — Eyeballs-down
Tailward — Eyeballs-up
Transverse
Lateral Right — Eyeballs-left
Lateral Left — Eyeballs-right
Back to Chest — Eyeballs-in
Chest to Back — Eyeballs-out
Note:
The accelerative force on the body acts in the same direction as the arrows.
Voluntary Exposure
Deceleration, g
100
50
20
10
5
2
1
.01
.02
.03
.04
.05
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Duration, seconds

Figure 1

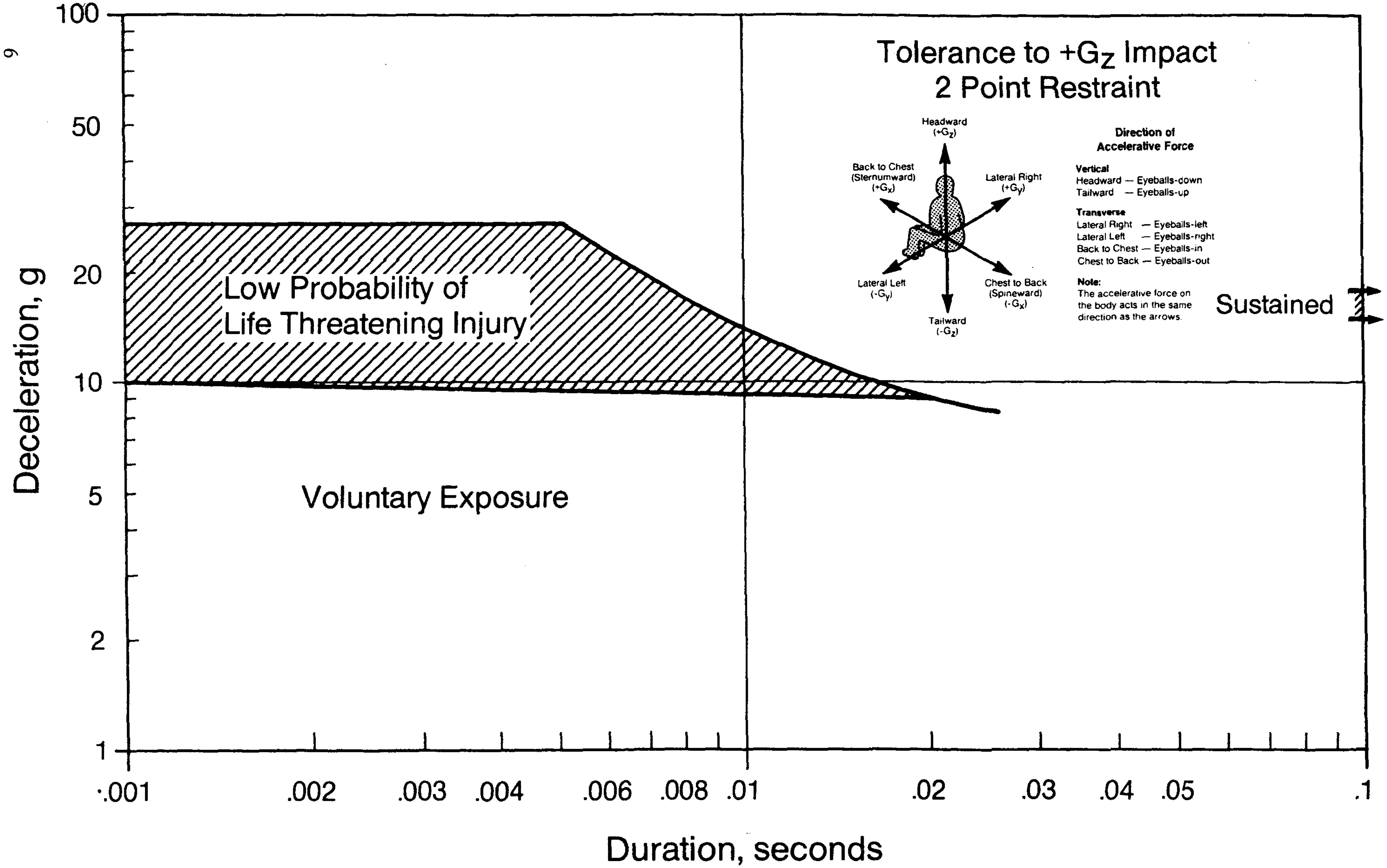
Tolerance to +Gz Impact
2 Point Restraint
Headward (+Gz)
Back to Chest (Sternumward) (+Gx)
Lateral Right (+Gy)
Lateral Left (-Gy)
Chest to Back (Spineward) (-Gx)
Tailward (-Gz)
Direction of Accelerative Force
Vertical
Headward — Eyeballs-down
Tailward — Eyeballs-up
Transverse
Lateral Right — Eyeballs-left
Lateral Left — Eyeballs-right
Back to Chest — Eyeballs-in
Chest to Back — Eyeballs-out
Note:
The accelerative force on the body acts in the same direction as the arrows.
Sustained
Low Probability of Life Threatening Injury
Voluntary Exposure
Deceleration, g
100
50
20
10
5
2
1
Duration, seconds
.001
.002
.003
.004
.006
.008
.01
.02
.03
.04
.05
.1

Figure 2

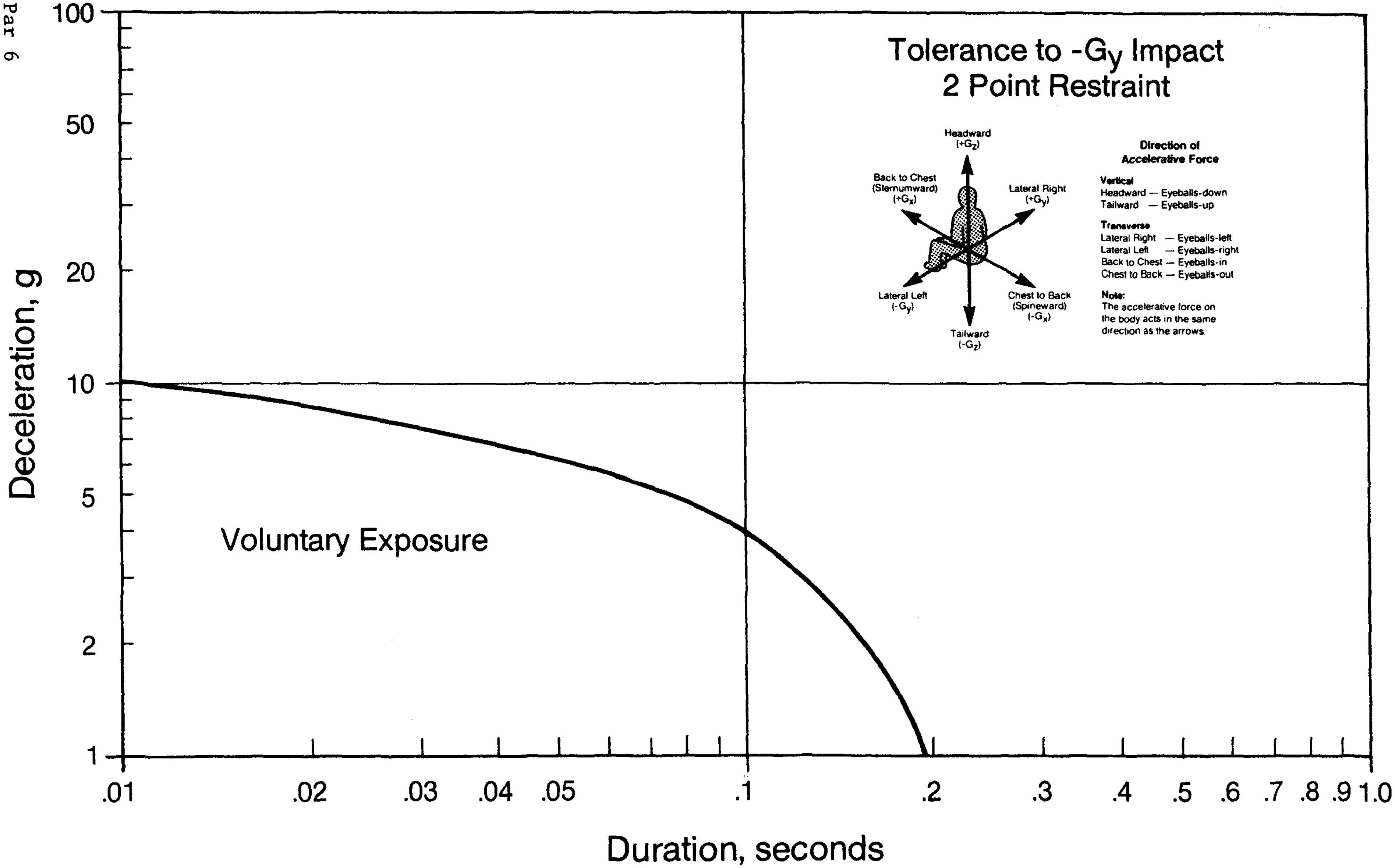
Tolerance to -Gy Impact
2 Point Restraint
Headward (+Gz)
Back to Chest (Sternumward) (+Gx)
Lateral Right (+Gy)
Lateral Left (-Gy)
Chest to Back (Spineward) (-Gx)
Tailward (-Gz)
Direction of Accelerative Force
Vertical
Headward — Eyeballs-down
Tailward — Eyeballs-up
Transverse
Lateral Right — Eyeballs-left
Lateral Left — Eyeballs-right
Back to Chest — Eyeballs-in
Chest to Back — Eyeballs-out
Note:
The accelerative force on the body acts in the same direction as the arrows.
Voluntary Exposure
Deceleration, g
100
50
20
10
5
2
1
.01
.02
.03
.04
.05
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Duration, seconds

Figure 3

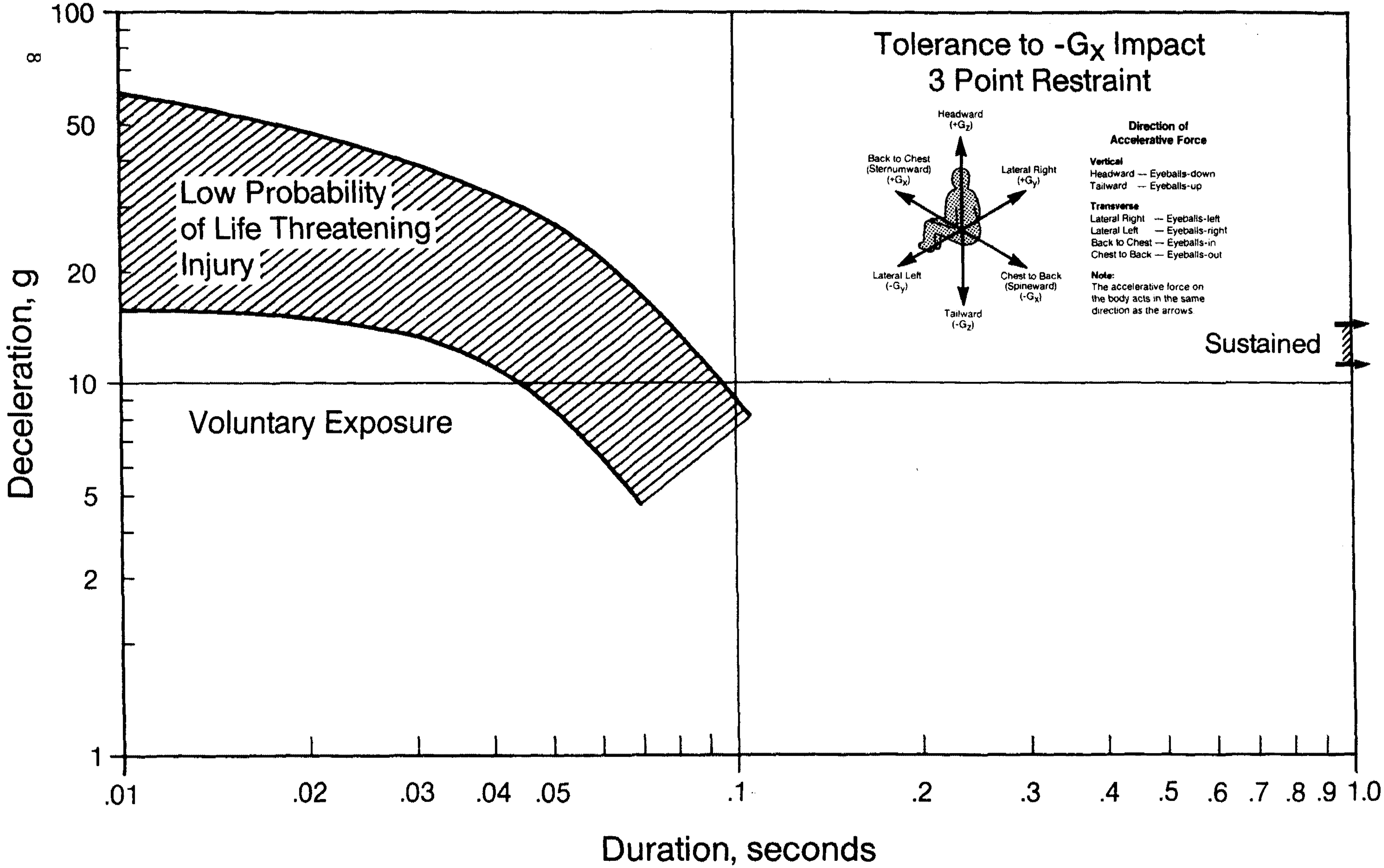
Tolerance to $-G_X$ Impact
3 Point Restraint
Headward ($+G_z$)
Back to Chest (Sternumward) ($+G_x$)
Lateral Right ($+G_y$)
Lateral Left ($-G_y$)
Chest to Back (Spineward) ($-G_x$)
Tailward ($-G_z$)
Direction of Accelerative Force
Vertical
Headward — Eyeballs-down
Tailward — Eyeballs-up
Transverse
Lateral Right — Eyeballs-left
Lateral Left — Eyeballs-right
Back to Chest — Eyeballs-in
Chest to Back — Eyeballs-out
Note:
The accelerative force on the body acts in the same direction as the arrows.
Sustained
Low Probability of Life Threatening Injury
Voluntary Exposure
Deceleration, g
100
50
20
10
5
2
1
.01
.02
.03
.04
.05
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Duration, seconds

Figure 4

of acceleration as a factor in injury. In short duration accelerations, such as occur in impacts (less than 0.02 seconds, for example), the injury limit is body structural, and this limit would be expressed better in terms of stress or strain. In any event, it should be understood that there are no universally accepted handbook values for impact injury criteria in the sense that there are handbook values for the properties of materials used in the construction of aircraft. Injury is a progressive occurrence, and the rate of progression varies with a number of factors which have not yet been completely understood. Also, impact injury criteria are not design criteria in the sense that they can be used during the design of an aircraft in the same manner as the properties of materials are used. Instead, such injury criteria should be viewed as test measurements which can be used to determine if an impact protection system is likely to have achieved some level of success. If a minimum level of protection has been established by regulatory requirements, as has been generated either by the rulemaking process for the automotive industry or by military specifications for defense suppliers, then the criteria and methods of demonstrating compliance with those criteria are defined. In the absence of such a definitive process, the responsibility for the selection of injury criteria pertinent to a particular application and for the development of appropriate test procedures to demonstrate that the injury criteria have been met falls on the manufacturer of the system. To assist in this effort, the following subparagraphs summarize some of the more important concepts for injury criteria which may, depending on the application, be of importance in the development of impact injury protection systems for civil aircraft. Other concepts, as well as arguments for and against most of the concepts presented here, can be found in the literature.

(1) Head Injury. Injuries to the head can be fractures or concussions. The mechanism of injury depends on the energy of the impact, the rotational and translational movement of the head relative to the body, the characteristics of the impacted surface (area, shape, and load distribution properties, for example), and the site and direction of the load (force) vector relative to the head. The Wayne State University Concussion Tolerance Curve (WSUCTC), proposed by Lissner, et al., in 1960, forms the basis for most current head injury criteria. Gadd devised a weighted impulse criterion to define a Severity Index (GSI) to represent the WSUCTC, so that a GSI less than 1000 represented the limit for skull fracture from localized impacts against a hard surface, and a GSI less than 1500 represented a concussion injury limit for distributed or non-contact blows to the head. An alternate representation of the WSUCTC, suggested by Versace, led to the Head Injury Criterion (HIC) specified in Federal Motor Vehicle Safety Standard (FMVSS) No. 208. The HIC requires a measurement in g's of the resultant acceleration at the center of mass of the head to be inserted into the following equation:

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\,dt \right]^{2.5} \right\}_{max} < 1000$$

where a(t) is the time history of the acceleration at the center of mass of the head measured with a system having a frequency response of 1000 Hz, t_1 and t_2 are the initial and final times (seconds) during a pulse interval, and a value of 1000 is the limit for head injury. Although usually not specified in the criterion, this limit is most useful with pulse intervals not greater than 0.05 seconds.

(2) Chest Injury. Upper torso injuries include both skeletal and soft tissue injury mechanisms. Neathery suggested that chest deflection showed good correlation with blunt frontal impacts and recommended a sternal deflection limit of 75 mm for representing severe, nonlife threatening, chest injury for a 45 year old mid-sized male. The primary problem with a deflection measurement is in making a single measurement which is descriptive of the complex thorax behavior under all conditions of impact. The same problem exists with a single acceleration measurement, such as used in limits which state "...shall not exceed 60 g's except for intervals whose cumulative duration is not more than 3 milliseconds," and is compounded by the difficulty of correlating an acceleration measurement with injury. Eppinger suggested an alternate, easily measured criteria, shoulder belt load, as a means of predicting thoracic fractures in cadaver tests (with consideration of cadaver weight and age at death). He suggested that a 5.8 to 6.7 kilo newtons (kN) upper torso diagonal belt force would produce the minimum average number of fractures in the automobile fatality population in a 13.4 meters/second (m/s) frontal crash with a particular belt restraint system. This approach is conditioned by the understanding that belt loads are also strongly influenced by belt geometry, a factor not represented in the analysis.

(3) Abdominal Injury. The clinical literature provides extensive documentation of the serious, life threatening injuries which can result from blunt abdominal trauma; however, the research accomplished to date to define abdominal injury criteria has been limited, and no practical criteria have evolved. Thus, considering the potential severity of abdominal loading, the only suitable recommendation is to avoid applying loads to the abdomen. In particular, a safety belt should be designed so that it does not slip from the pelvis to the abdomen.

(4) Leg Injury.

(i) Early studies by Patrick, et al., used embalmed cadavers with head, chest, and knees striking lightly padded load cells during sled tests. They concluded that a load of 6.2 kN represented a conservative value for overall injury threshold for the patella-femur-pelvis complex. More recent studies by Melvin, et al., using unembalmed cadavers and an impactor with 25 mm of energy absorbing padding, indicated a threshold of fracture of 13.3 kN, with a threshold impactor momentum of 180-220 Ns necessary to cause fracture. The current limit specified in FMVSS 208 is 10 kN which is suggested as being appropriate criteria in aircraft. These studies concerned impacts which were essentially in line with the femur.

(ii) Concentrated loading of the patella by impactors having circular or ring shapes less than 16 mm in diameter demonstrated failures as low as 2.5 kN, with patella damage varying dramatically with impact velocity.

(iii) Transverse loading of the lower leg was reported by Young to result in tibia fracture at force levels from 4.45 to 6.67 kN. Kramer, et al., found a 50 percent fracture limit of the lower leg to lie between 3.3 and 4.4 kN, depending on the diameter of the impacting cylinder.

(5) Spinal Injury.

(i) Damage to the vertebral column, particularly to the upper lumbar and lower thoracic segments, occurs frequently where severe impact force is directed parallel to the spine. Stech and Payne modeled this impact as a single lumped-mass, damped-spring system, assuming that the total body mass which acts on the vertebrae to cause injury can be represented by one rigid mass. The model is used to predict the maximum deformation and the associated force of the spring (representing the vertebral column) for an input acceleration-time history measured on the structural seat pan of an ejection seat. The injury criterion which results is called the Dynamic Response Index (DRI). DRI limits for uniaxial spinal compression fractures of military aircrew have been suggested as follows:

DRI = 18.0 implies less than 5 percent risk of injury
DRI = 20.4 implies less than 20 percent risk of injury
DRI = 23.0 implies greater than 50 percent risk of injury

While the DRI has been successfully used for several military programs, these programs have also used well designed restraint systems to avoid bending loads on the spinal column which are not always possible in civil systems. Moreover, few civil aircraft seats have well defined structural seat pans on which respresentative accelerations can be measured. In an attempt to overcome these problems, Chandler conducted tests using a modified Part 572 ATD with a load cell inserted into the pelvis at the base of the rubber "lumbar" cylinder of the dummy. He found that, under a variety of test conditions with a military type seat, a pelvic compression load of 6.7 kN correlated with a DRI of 19, indicating a low to moderate risk of injury. Since loads from the restraint system which would cause spinal compression would most likely be reflected in an increased pelvic load, this measurement may have more general application and is suggested for use in aircraft.

(ii) Models which are, in effect, limited to one injury indicator for spinal column injury cannot predict the complex stress distribution which exists in this complex structure. Several more sophisticated models have been suggested, but there is no general consensus of more representative injury criteria. In any event, the measurements which can be made during a test will probably limit any proposed criteria to axial and shear loads and moments and torque in practice.

d. Restraint Effectiveness and Other Criteria. There are several other criteria for effective protection against impact injury which cannot be defined by numerical limits. Among the more important of these are:

(1) Restraint systems should be designed to encourage frequent and proper use by occupants. Restraints which are complex, uncomfortable, or unduly restrictive to normal operational functions of the occupant are unlikely to be successful.

(2) Restraints should fit the size range of occupants that are likely to use the system. Misfit restraint systems can cause injury; for example, a diagonal belt which bears against the side of the head can promote neck injury if vertical impact takes place; a diagonal belt which passes below the center of mass of the upper torso-head-neck complex may allow the torso to rotate out of the restraint and increase the potential of either impact with the aircraft interior or injury from spinal column torque, etc.

(3) Restraints should apply loads to the body areas most able to withstand the loads (i.e., pelvis or shoulders), and should not move from those areas during the impact.

(4) Seats and restraints should distribute their load over a maximum body contact area to reduce concentrated load on the body.

(5) Seat and restraint systems should provide as much uniform load distribution to the body as possible to limit relative displacement of the body segments.

(6) Elasticity of elements in the restraint and seat allows body motion and can increase impact severity. For example, long lengths of restraint webbing stretch more than short webbing lengths and allow more occupant motion.

e. Accepted Injury Criteria. The following documents contain injury criteria and test procedures which have been accepted by user groups and have served as guidance for establishing similar criteria for civil aircraft crash injury protection systems:

(1) Federal Motor Vehicle Safety Standard No. 201, Occupant protection in interior impact (49 CFR 571.201), contains criteria for head impact with instrument panels and seat backs.

(2) Federal Motor Vehicle Safety Standard No. 202, Head restraints (49 CFR 571.202), contains criteria for head restraints intended to reduce neck injury in rear-end collisions, and may be applicable to rear facing seat, head rest design in aircraft.

(3) Federal Motor Vehicle Safety Standard No. 203, Impact protection for the driver from the steering control system (49 CFR 571.203), contains criteria to minimize chest, neck, and facial injuries resulting from impact with the steering control.

(4) Federal Motor Vehicle Safety Standard No. 208, Occupant crash protection (49 CFR 571.208), contains criteria for the head, thorax, and upper legs to minimize injury in an automobile crash.

(5) Military Specification 58095(AV), General Specification for Crashworthy, Non-Ejection, Aircrew Seat System (MIL-S-58095(AV)), contains specifications for limiting spinal injury created by whole body vertical acceleration.

f. Suggested Numerical Values for Aircraft Use. The following subparagraphs summarize the impact injury data that are suggested herein for use in assessing the performance of impact injury protection systems in civil aircraft, and these data are not to be considered as regulatory criteria. It is not intended that all of the suggested performance criteria should be used in every case to assess each impact injury protection system. When regulatory requirements are established, specific performance criteria will be defined within the rule. In such cases, the regulatory criteria take precedence over anything presented in this advisory circular. In the absence of a definitive regulatory requirement though, a manufacturer should select appropriate performance criteria, develop appropriate test procedures for the particular application, and demonstrate that the selected performance criteria have been met.

(1) Whole body impact tolerance —

(i) $-G_x$ (2-point restraint) Figure 1

(ii) $+G_z$ (2-point restraint) Figure 2

(iii) $-G_y$ (2-point restraint) Figure 3

(iv) $-G_x$ (3-point restraint) Figure 4

(2) Head injury — HIC < 1000 ($t_2-t_1 < 0.05$ seconds)

(3) Chest injury — Diagonal shoulder belt load - 7.8 kN (1750 lbs.)

(4) Abdominal injury — No quantitative data suggested.

(5) Leg injury —

(i) In line with femur - 10 kN (2250 lbs.)

(ii) Patella (concentrated load) - 2.5 kN (560 lbs.)

(iii) Transverse (lower leg) - 4.45 kN (1000 lbs.)

(6) Spinal injury — Pelvic compression load - 6.7 kN (1500 lbs.)

J. A. Pontecorvo
Joseph A. Pontecorvo
Deputy Director of Airworthiness