Tolerable Severity Index in Whole-Head, Nonmechanical Impact

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HUMAN TOLERANCE to abrupt $-g_x$ acceleration was conservatively represented in an NASA report in 1959 (1)* as a curve of tolerable acceleration pulses which diminished as the duration of the pulse increased. In Cartesian coordinates the curve tended toward a horizontal asymptote at long duration, but on a log-log scale a straight line at $-1/2.5$ slope could be drawn midway between the "injured" and "uninjured" lines out to about 1 s duration as shown in Fig. 1. In a later NASA human tolerance literature summary reported in 1966 (2), this same falling trend of tolerance was shown to extend to even longer duration. Data points and bounds given therein for maximum volunteer tolerance using harness or couch support are also transcribed in Fig. 1. Decelerations with automotive restraint systems extend only out to the order of 0.1 s, and therefore, the points beyond are of interest chiefly in illustrating the general falling trend of tolerance with time, considering all injury mechanisms.

This continually falling trend of tolerance is also reflected by tests of primates of various sizes. The Sonntag chimpanzees (3) sustained 20 ms plateau g values of 149 with no injury, whereas the same type of primates in Ref. 4 could sustain 150-350 ms plateaus of only 80-90 g. Going to the monkey family, even the larger species have been shown by various investigators to be able to tolerate over 1000 g at short duration, while the small squirrel type (whose g tolerance should generally be greater by virtue of its smaller size) was able to withstand only $\pm 50\ g_x$ at 300-400 s (5).

Prior to the first NASA report, the Wayne State investigators had shown a broad band of data points indicating a falling tolerance to head injury as pressure pulses of increasing duration were applied to the living canine brain. Their early skull fracture studies (6), as well as their most recent (7), have provided in addition an "anchor point" for the short-duration end of a 2.5 power curve. The Severity Index concept corresponding to a tolerance borderline at $-1/2.5$ slope was a generalized representation of data from both NASA and Wayne State.

A question has existed, however, regarding just how conservative is a Severity Index of 1000 for various pulse durations. In hard impact of a few milliseconds

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*Numbers in parentheses designate References at end of paper.

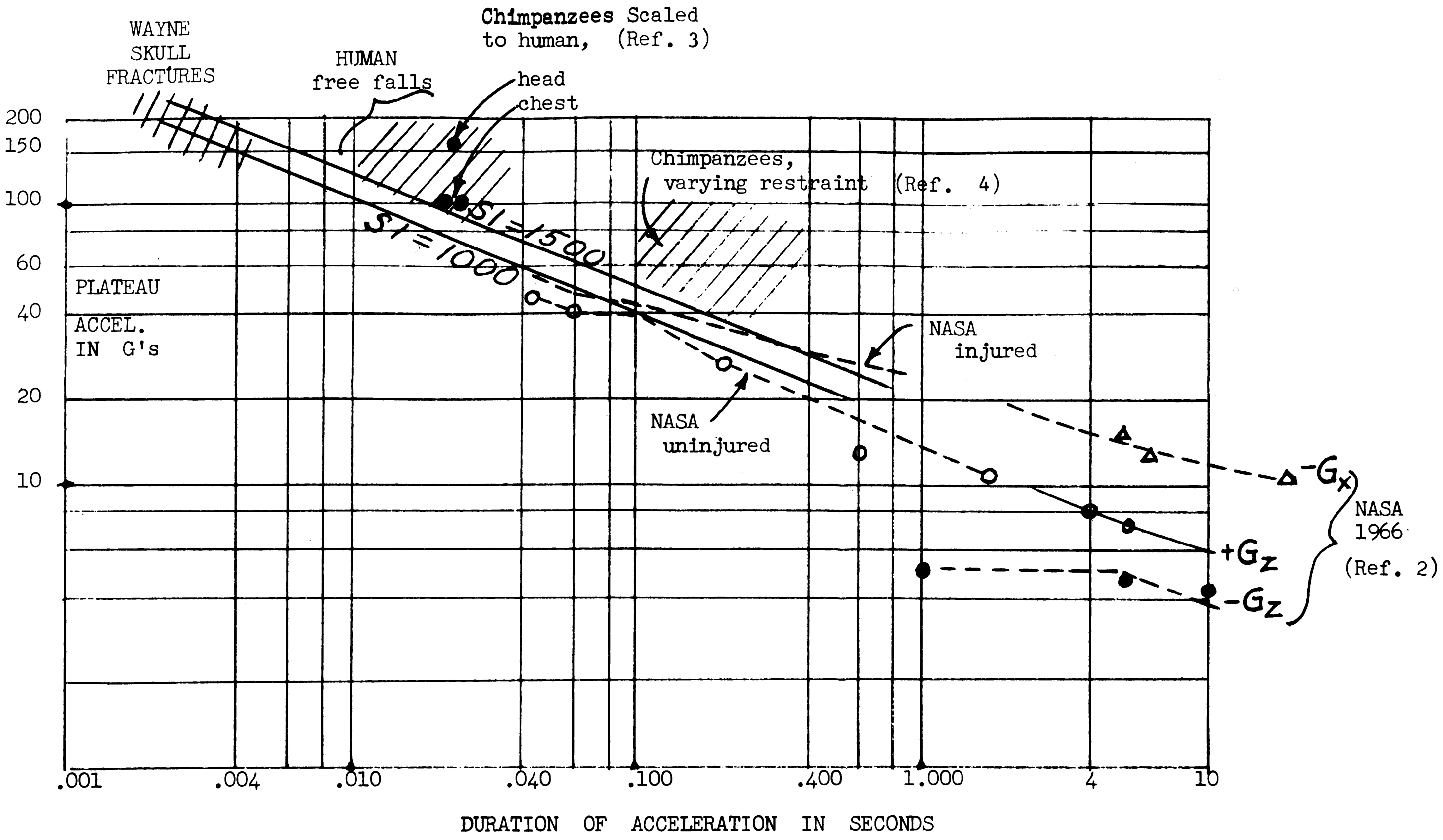


Fig. 1 - NASA 1959 and 1966 literature summaries for tolerable plateau accelerations, harnessed, with other data superimposed

entailing skull fracture hazard, there appears to be little biomechanical factor of safety at an Index of 1000. On the other hand, the possibility suggests itself that in whole-head acceleration involving no mechanical impact (for example, when a car occupant is restrained by a harness or air cushion), the use of a Severity Index greater than 1000 is logical. This would be analogous to the accepted engineering design practice of employing a lower factor of safety in the absence of localized loading capable of producing concentration of stress.

An objective of this discussion is to examine more recently available data from the standpoint of usage of a higher Severity Index under whole-head acceleration exposures free of mechanical impact. It should be emphasized that this discussion will relate to biomechanical tolerance values applicable as design goals rather than to Motor Vehicle Safety Standards limits. It is felt that the latter should be higher than the former since they should make allowance for unavoidable accumulation of variances in a given experimental test due to vehicle variations, test variations, and dummy deficiencies.

A second objective will be to call attention to past experiments which if analyzed in more detail will shed further light on human tolerance, as well as to cite new research which it is felt will be needed before head tolerance can be specified more precisely. Following are a number of what are believed to be worthy study areas.

Whole-Body Animal Experiments

Those of Sonntag (3) are perhaps of greatest interest in that the chimpanzees were stopped from 90 mph in only 28 in without appreciable injury. If one scales the 149 g plateau to the human by the simple $1/\ell$ inertial scaling factor (which assumes loading is in proportion to inertia force but stresses vary inversely with cross-sectional areas, and which is believed most logical at this time for closed-skull translational loading), one obtains slightly over 100 g. Then, allowing for the ramps on the deceleration profile needed to bring the total ΔV to 90 mph, a Severity Index of approximately 2000 is indicated for the human being. According to Stapp (8), the chimpanzee's head actually reached 239 g in these tests, evidently as a result of amplification of head acceleration occurring in spite of the muzzle strap, so that the predicted Severity Index for the human should be well over 2000.

Air Force Rocket Sled Experiments

These and the volunteer Daisy Track tests mentioned below are among the most interesting and fruitful areas for more detailed study. When reported by the NASA and others, only a nominal or whole-body tolerance was given as a rule without taking into consideration any amplification of head movement with respect to the restrained torso and without considering the rising and falling ramps of the g-time profiles. Since laboratory accident experiments generally involve the recording of at least the two major components of head acceleration (a-p and s-i), it would seem only proper to go back to the human experiments and estimate as closely as possible the biaxial or triaxial resultant exposures actually sustained. If this can be done, it would be preferable to simply stating that the nominal tolerance values are conservative.

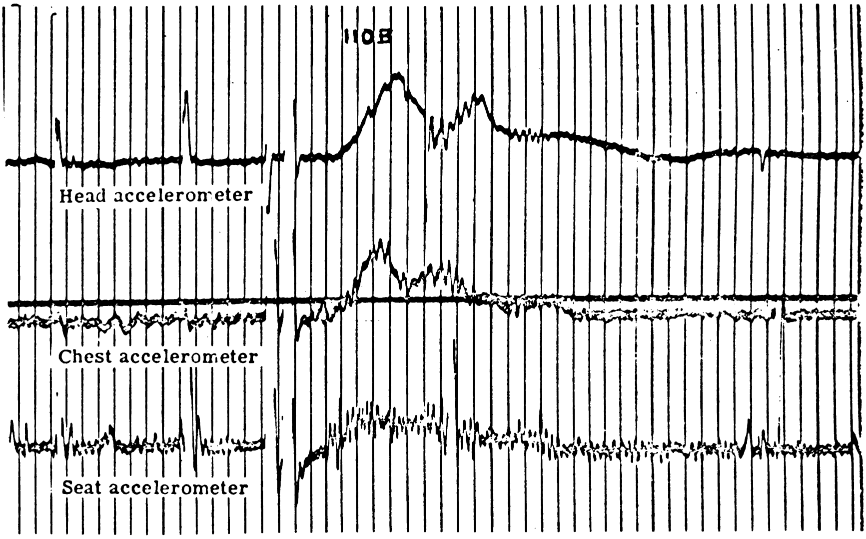
In this short discussion, a preliminary look is taken at some of the original rocket sled runs from this standpoint. It is recommended that this be followed by more thorough studies which would entail reconstructing the same conditions by a Cornell type math model or by field testing with dummies and using high-speed films of the original volunteer tests to insure proper simulation of head and chest excursions.

Run 110 - Fig. 43 of Ref. 9 gives very good quality traces of a-p accelerations of both head and chest sustained by Col. Stapp on this, one of his less severe runs. Total exposure was 150 ms but with the bulk of it limited to about 75 ms with peak acceleration of the head of 48 g. In this, as in the other runs of the program, the volunteers followed a policy of holding their heads forward with chin against chest and as rigidly as possible in order to minimize neck injury or chin-chest impact. Integrating the head g-time trace of Fig. 43 directly gives a Severity Index of approximately 550; but assuming that the head accelerometer reads only a 45 deg component of the resultant of a-p and s-i acceleration, the peak g can be estimated to have been 68 g with an actual Severity Index, if it had been read biaxially, of approximately 1200. Run 111 was similar to run 110 but more severe (ΔV was 73 rather than 57.3 mph) in same time period. The head and chest oscillograms of both of these runs are reproduced as Fig. 2 of this discussion.

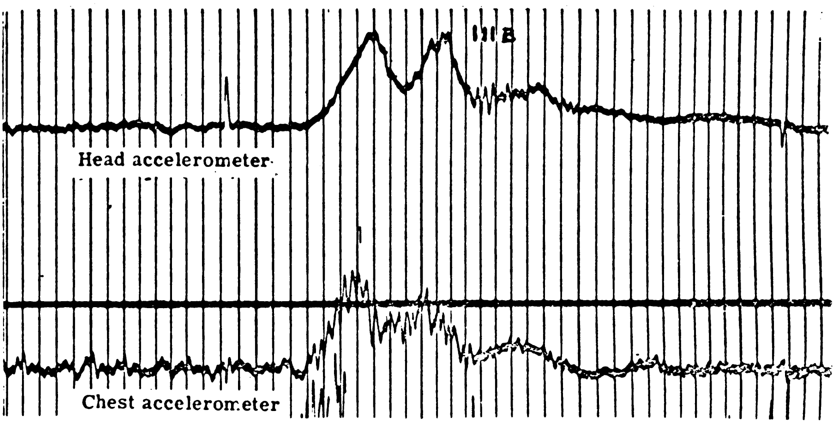
Run 215 - This well-known run of Col. Stapp with a sled g of 45 is documented extensively in Ref. 9 in terms of seat, chest, and a-p mouth acceleration. Also, plots of head rotation and shoulder displacements versus time are taken from the high-speed movie coverage. The head angulation was seen to remain within ten degrees of a nominal 45 deg forward angle over the entire deceleration period. The head g-versus-time trace, Fig. 121 of Ref. 9, integrates to a Severity Index of about 650; but if one applies the correction factor of 1.414 to the 2.5 power to allow for the forward attitude of the mouth accelerometer, the true biaxial head exposure can be estimated to have been approximately 1500.

Run 133 and Repeat Run 135 - These two most severe runs of the series employed more severe braking with a sled plateau g determined to be between 38 and 39. In both runs, however, a violent overshoot of the torso with respect to the seat was reported. The subject was reported to have "hit all parts of the harness with extreme violence," and sustained soreness, multiple contusions, and abrasions under the harness contact areas. The NASA report, Fig. 34 of Ref. 1, estimated an amplification of chest g as compared with sled g of approximately 1.6:1 for these high-rate-of-onset runs as a result of the subject-harness system tending to "tune in" with the applied sled pulse. This would have placed the torso g at a little over 60. The oscillograms of Fig. 68, while incomplete, showed that torso loading occurred essentially over a period of about 70 ms. Although these runs could be reconstructed more accurately by mathematical modeling, it is reasonable to estimate the Severity Index based on chest g's to have been at least 800. (Brinn (10) estimated the sled SI to have been 589.)

Biaxial head g would in both runs have been higher than chest g. Run 133, however, is of special interest because it undoubtedly entailed an even greater



RUN No. 110 - 57.4 mph ΔV in 0.15 SEC.; 31.8 Sled g Plateau



RUN No. 111 - 73 mph ΔV in 0.15 SEC.; 34.6 Sled g Plateau

Fig. 2 - Comparison of two runs from Ref. 9

amplification of head Severity Index. In this most injurious run of the entire series, it was stated (p. 96) that the "subject failed to follow instructions to keep his head down," and his helmet flew off during the deceleration; and he lapsed into unconsciousness for a short period after the run. In repeat run 135, with head held down to avoid amplification of head loading, the new subject (JPS) did not suffer unconsciousness. Whereas, in the latter run, the biaxial Severity Index should have been at least 1500; the more violent head movement of run 133 should have produced an even higher value.

Daisy Track Series

Detailed study of the high-speed films of the forward-facing runs of this series should shed more light on true tolerance of the head to short-duration biaxial acceleration. These tests, conducted under the direction of Eli Beeding in 1960, showed that volunteers restrained by a modified Air Force harness which securely held the torso could be decelerated from 46 ft/s to zero in between 60 and 70 ms, even though the head was unrestrained and free to whip forward violently during the deceleration. Average rate of onset or slope of the sled g profile reached 1040 g/s in this series, together with plateau sled g of 34, according to Ref. 8 and other reports of this series. It is hoped that the tests can be thoroughly analyzed from the standpoint of maximum biaxial head acceleration sustained.

Laboratory Barrier Crash Simulations

These, together with knowledge of survivability in field accidents, constitute a valuable potential source of head acceleration tolerance data. Recent studies (11) indicated that harnessed car occupants can usually survive the equivalent of a 30 mph barrier accident. Once anthropomorphic dummies can be made to simulate the human faithfully, it should be possible to estimate by this independent means the highest multiaxial Severity Index levels which can be tolerated. From work thus far it can be said that, on a relative basis, combined a-p and s-i head Severity Index or g levels at the head are generally substantially greater than those of the chest. This has been true over a considerable range of dummy neck constructions or adjustments. Even though accident reconstruction is at only an early stage of development as a source of human tolerance data, it does indicate biaxial Severity Index values well over 1000 can be tolerated by harnessed individuals.

Human Free Falls

A cross-hatched band between 100 and 200 g and 10-40 ms duration has been indicated in Fig. 1 in recognition of the belief on the part of various recognized biomechanics specialists that extreme free-falls are representations of the maximum survivability which is possible providing severe localized loading of key regions of the body is avoided. Many of those survivals have been from great heights (for example, from 10th to 14th story windows). While the 100-200 g band is that estimated by various investigators for the more severe falls, a fruitful area of research would be to reconstruct certain representative cases by the use of a sophisticated dummy to obtain a better estimate of minimum head or chest g-time histories which must have been sustained.

General Comments

Some investigators have felt that a head tolerance curve should reach a true horizontal asymptote even when plotted on log-log scales. This, however, has been on the assumption that some particular mode of dynamic strain is involved, either in the form of an inertial movement of the brain as a single rigid mass or a transient vibration of the skull. The writer believes it is important to realize that this differential equation used as a math model can represent only one or the other of these, but not both, since different coefficients would be involved. A mathematical scaling procedure is also so limited.

The writer feels, on the other hand, that the real existence of many modes or distributions of strain, as well as many sites and types of injury within the head, must be recognized. (Each issue of the HEW periodical, "Classified Bibliography of Recent Head Injury Literature," for example, contains a large number of new titles in its sections of Basic Mechanisms.) Thus, the general tolerance band of Fig. 1 may have hidden within it certain "shelves" for particular mechanism. But very little, if any, evidence exists to support the existence of such shelves or plateaus as a measure of general head tolerance for the spectrum of occupants and situations for which the vehicle must be designed. This appears especially true in view of how little is known yet of the relative hazard of different components of acceleration (for example a-p, s-i, i-s, and rotational) or of accumulative effects of double pulses or positive and negative portions of a pulse.

It must be acknowledged that additional data may point to departure from the simple exponential approximation, and the writer believes research should be directed toward such refinement, including critical experiments which may differentiate between differing theories. Two possibilities may be envisioned. If it is shown that the brain behaves essentially as a semiviscous body relatively free of dynamic response, the exponential weighting should suffice with the addition if needed of a variable exponent as suggested by J. Danforth. On the other hand, if dynamic response proves to play an important role, this may be taken into consideration in a general sense (not limited to a simple one- or two-mass system) by the shock spectrum approach as suggested by P. Remmers in discussion at the 14th Stapp Conference.

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