Human Tolerance to Positive G as Determined by the Physiological End Points

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WITH the construction of a centrifuge capable of rapid acceleration to high levels of *g*, it became possible to extend the experimental range of investigation of human tolerance to positive *g* to levels previously unattainable. Such experiments have been carried out in this laboratory by Beckman, Duane, Ziegler and Hunter.[1,6] It is the purpose of this report to present an analysis of the original experimental data obtained by these investigators, and to compare and integrate these results with those observed in other laboratories.

MATERIALS AND METHOD

The centrifuge itself and its performance capabilities have been described.[3,7] Briefly, it is pertinent to this study that the instrument is capable of producing up to 15 *g* within 1.5 seconds and that the patterns of acceleration used in the present study were produced by use of cams which automatically controlled the performance of the centrifuge. Thus, the time required to reach a desired *g* level, the *g* level itself, and the time for which it was maintained constant were precisely controlled and each pattern was reproducible at will. The patterns chosen covered a wide range of acceleration rates and levels of *g* productive of the physiological end points of grayout, blackout, extreme confusion with possible unconsciousness, and complete unconsciousness. As previously described,[1] the end points were bracketed with respect to *g* level and time by increments of 0.5 *g* in the height of *g* force attained and 0.5 - 0.25 second in the time of exposure to the maximum *g* force. *G* level, subject responses, and time were recorded automatically. Recorded responses to peripheral and central light signals, verbal reports taken at the conclusion of each run, and objective evaluations made by the observers (*e.g.*, complete unconsciousness at the end of the run) were used in determining the effect of each exposure.

The method of analysis employed was based upon the usual concept of a physiological response brought about by a stimulus characterized by intensity and duration such that the zone of response may be separated from the zone of no response by a simple stimulus strength-duration curve. Thus, the intensity of the stimulus productive of an end point was measured in *g* units, and the duration was measured in seconds of exposure to the accelerative force. Unlike the usual practice in *g* studies of expressing stimulus duration as the time of exposure to maximum *g* only, in this analysis duration was taken as the entire time from the effective start of acceleration to the end of exposure to maximum *g* (or the beginning of deceleration) as illustrated in Figure 1A. The slope of

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the best straight line drawn along the rising portion of the g trace was taken as the rate of acceleration. The point of intersection of this line with the time axis was taken as the effective start of acceleration, and the time from this point to the point of intersection of this line with the extended peak g line was taken as the rise time and the beginning of the time at maximum g. It is recognized that it might not be proper to include all of the rise time in the duration time since this assumes an instantaneous rise to maximum g which is not in fact accomplished. Probably some fraction of the rise time (as in Fig. 1B) would be more accurate. Also, at very slow rates of acceleration, as well as at very high rates of acceleration, the time at maximum g before grayout, blackout, or unconsciousness occurs may be negligible (Fig. 1C) and the total time is then equal to the rise time. The precise determination of the coefficient of the rise time most appropriate for inclusion in the total tolerance time may be determined by comparison of the latter type of data with that obtained from the pattern shown in Figure 1B. However, data of this kind are at present insufficient to make this determination and a, the coefficient of the rise time, was taken as 1.0 for the purposes of this analysis. By employing a wide range of acceleration rates, it becomes apparent that time at maximum g is insufficient as a measurement of stimulus duration although it yields comparative data when the acceleration rate is fixed, or nearly so. Furthermore, the importance of the rise time is emphasized by the fact that arterial blood pressure begins to fall im-

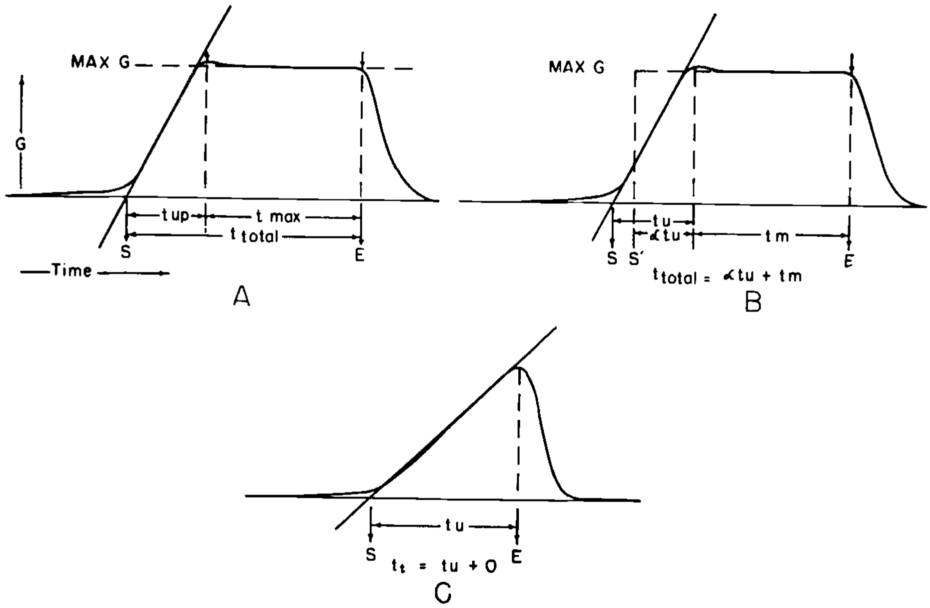

Fig. 1. G trace analysis

mediately upon application of the g force as illustrated in Figure 2, in which aortic blood pressure, measured by catheterization, in the unprotected

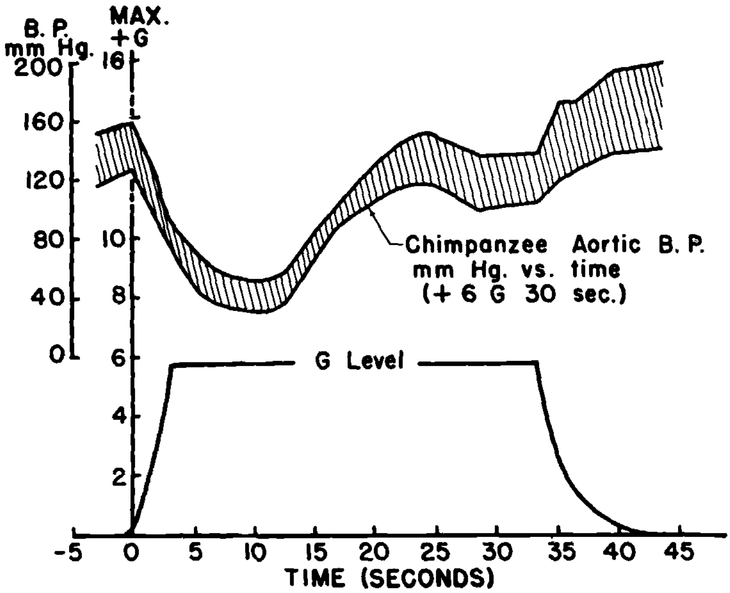

Fig. 2. Variation in chimpanzee aortic blood pressure with positive g.

anesthetized chimpanzee is plotted with the acceleration pattern productive of the pressure changes.[9] Not only does the pressure begin to fall immediately upon application of g, but also it is restored to normal in spite of a sustained force of 6 g and rises sharply above normal immediately upon reduction of this force, at the very beginning of deceleration. This pattern of blood pressure change has also been observed to some extent in the human subject.[8,10] although published data are scanty. Thus, it would appear that in relating stimulus to response, the time required to attain maximum g cannot be ignored, while the time required to return from the maximum level to 1 g does not contribute to the stimulus required to produce the physiological response even though the response be observed after the maximum g force has been reduced (during deceleration).

Original records of about 300 experiments on fifteen different subjects were available at this laboratory. The records of those experiments productive of a physiological end point were analyzed for: (1) the rise time (t_r); (2) the time at maximum g (t_m); (3) the level of maximum g; and (4) the rate of acceleration to maximum g. These data were then compared with respect to (1) intensity of g and total duration time and (2) rate of acceleration employed and total duration time.

RESULTS

Of the 300 experiments, only forty yielded definite physiological end points and data which could be used in this analysis. However, these forty points represent precise data since the intensity of the stimulus required to produce an end point was measured to ± 0.5 *g*, and the duration to ± 0.25 to 0.5 second by the approach of small increments of *g* and of exposure time.

The strength-duration relationship for positive *g*-tolerance as determined from these data is shown in Figure 3. It is seen that: (1) it conforms to that usually observed for physiological stimuli except in the region beyond about 10 seconds where the experimental curve (solid line) diverges from the value expected by extrapolation along the lines of the usual strength-duration (dashed line), (2) the relationship of *g* to time is most variable at times greater than six seconds, and (3) the spread of the data throughout the range of experimentation is such that the average stimulus required to produce unconsciousness overlaps that which is required for grayout or blackout alone.

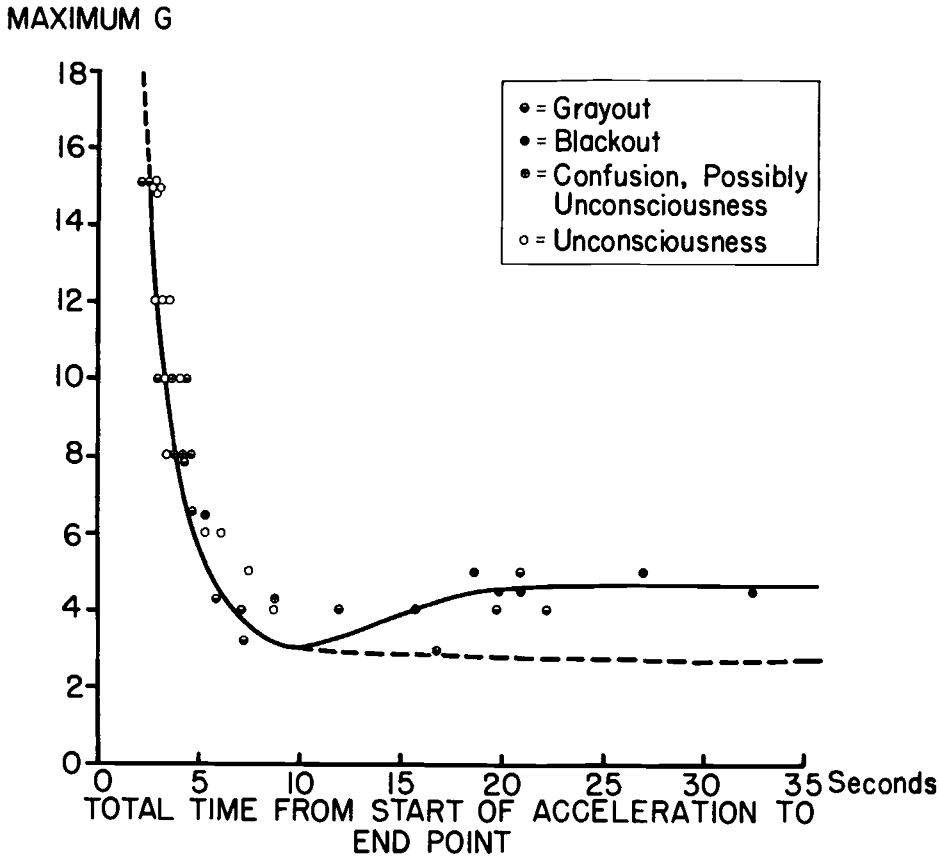

Fig. 3. Human tolerance to positive *g*.

Physiological Implications of Experimental Data.—The present data extend the region of actual experimentation with positive g in the upright seated position up to the 15 g level, an increase of at least 6 g over previous limits, attained in less than 2.5 seconds. This permits the extension of the tolerance curve well into the region preceding that in which cardiovascular reflex protection may be demonstrated. Thus, it is seen in Figure 3 that the tolerance curve is smooth, down to about 4 g at about 6-8 seconds. Beyond this area, the same or greater g levels may be sustained without unconsciousness and much variability is observed. This is consistent with the demonstrated effectiveness of cardiovascular reflexes which become apparent in 6-12 seconds after the start of acceleration[5,12] and varies widely from individual to individual and within the same individual from time to time.[11] The difference between the extrapolated value (dashed line) and the observed end points (solid line) may be considered to represent the advantage obtained from these reflexes.

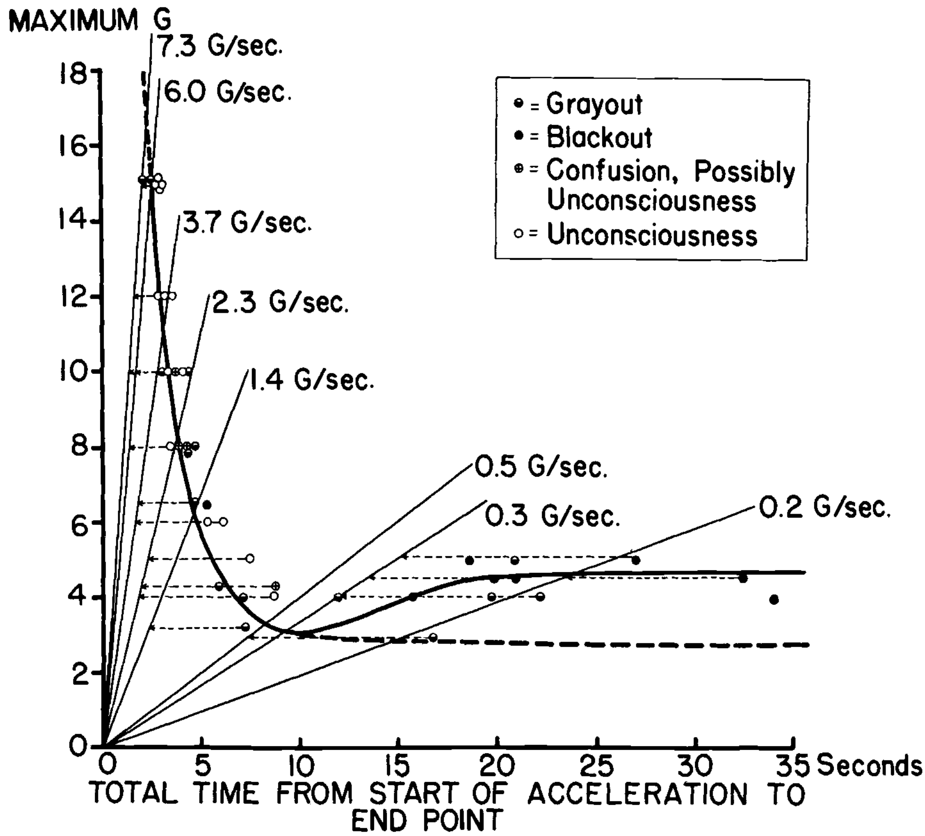

Fig. 4. G-tolerance curve with various acceleration rates.

In Figure 4, the rise part of the g curve was superimposed upon the tolerance curve. The end points produced are related to the appropriate rate of acceleration by means of dashed lines and arrows. Thus it is possible from this presentation to obtain directly from the chart the rate of acceleration, the time required to reach the g level, the g level itself, and the exposure time at maximum g for each experiment productive of an end point.

It is seen from this plot that both the time at maximum g and the total time vary inversely with the rate of acceleration employed, as well as with the g level attained. To determine the extent to which this correlation might be made, the rate of acceleration was plotted against the total time to the end point as shown in Figure 5. While there is still considerable overlap of points of grayout and of unconsciousness, particularly in the region of 6 g per second, it is evident that there is a greater time lag between grayout and unconsciousness at the lower rates of acceleration than there is at higher rates. This is as might be expected since greater stress is applied in a shorter time at higher rates of acceleration. This correlation suggested the construction of a nomogram which may be of practical service in indicating approximately the time for which a given level of g may be tolerated, provided that the rate of acceleration is known and constant. It is shown in Figure 6, constructed from the same data as that from which the tolerance curve was derived, and is entirely empirical, thus valid only within the

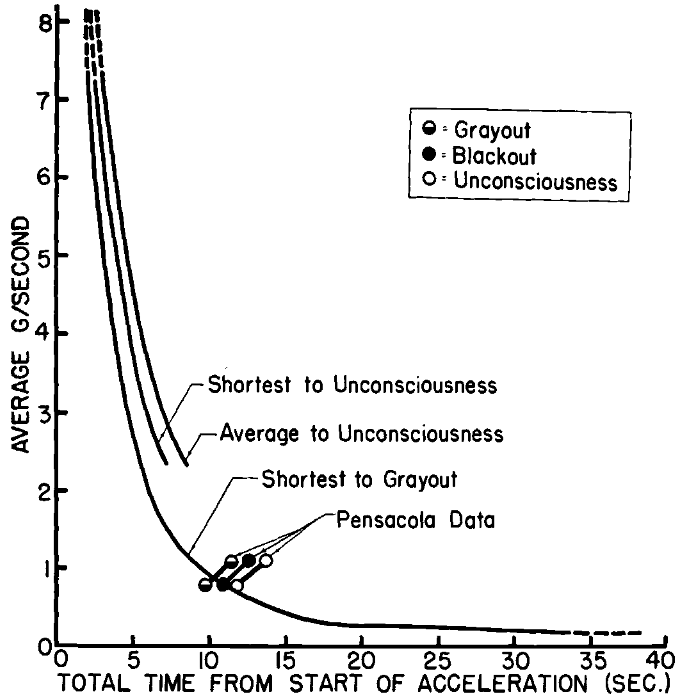

Fig. 5. Correlation of acceleration rates with time to end point.

limits of actual experimentation. In this chart, the rate of acceleration in g per second is shown on the abscissa in linear units and time is shown on the ordinate in log units and represents the time to grayout remaining after the g level indicated by the solid curves is attained at the corresponding rate of acceleration. Thus, in use, if the rate of acceleration employed is 3 g per second, then at the 6 g level, grayout occurs after about 2.7 seconds (a total of 4.7 seconds from the start of acceleration) and at the 8 g level, after about 2 seconds at 8 g.

TABLE I. CONSCIOUS TIME AFTER GRAYOUT RELATED TO ACCELERATION RATE

Acceleration Rate (g/sec.)	Time to Unconsciousness After Grayout	
	Shortest (seconds)	Average (seconds)
2.5	1.6	2.8
3.0	1.3	2.3
3.5	1.2	2.1
4.0	1.1	1.8
4.5	1.0	1.7
5.0	0.9	1.5
5.5	0.8	1.4
6.0	0.7	1.2
6.5	0.6	1.1
7.0	0.5	1.0

Treating the data in this manner brings out the interesting point that within the area where the elapsed time from the start of the run to the occurrence of grayout is less than about 4 seconds, attaining a given g level at lower rates of acceleration apparently permits a longer time at maximum g before grayout than does a faster rate of rise to the same g level. For example, attaining 6 g at a rate of 3.5 g per second, permits 2.5 seconds at 6 g before grayout, whereas at 6 g attained at 4.5 g per second, only 2.0 seconds remain before grayout. This bears upon the problem of the correct value for a, the coefficient of the rise time, which in this analysis has been assumed to be 1.0. It may well be that a is not a constant but is a variable, dependent upon the magnitude of the acceleration rate. Since this point can be settled only by experiment, the final statement awaits the results of further studies now in progress on the Aviation Medical Acceleration Laboratory centrifuge.

The time remaining between grayout and unconsciousness during acceleration at a constant rate may also be derived from the plot of the data in Figure 5 and is shown in Table I.

In the series considered here, no experiments in which the acceleration rate was less than 2.5 g per second were carried to the end point of unconsciousness. However, in a series of 1,000 experiments conducted at the U. S. Naval School of Aviation Medicine, in which the acceleration rate used was about 1 g per second, the mean time from grayout to blackout was found to be about 2 seconds. A plot of these data is seen superimposed on the curve in Figure 5. The symbols indicate the end points observed and are plotted to show the mean values obtained at the lowest (0.8 g per second) and the highest (1.1 g per second) rates of acceleration used.

Comparative Experimental Data.—Undoubtedly, forty experimental points are rather few to establish a general tolerance curve and to form a basis for prediction of tolerance under given acceleration stress. It is anticipated that with more data available, adjustments of mean values may

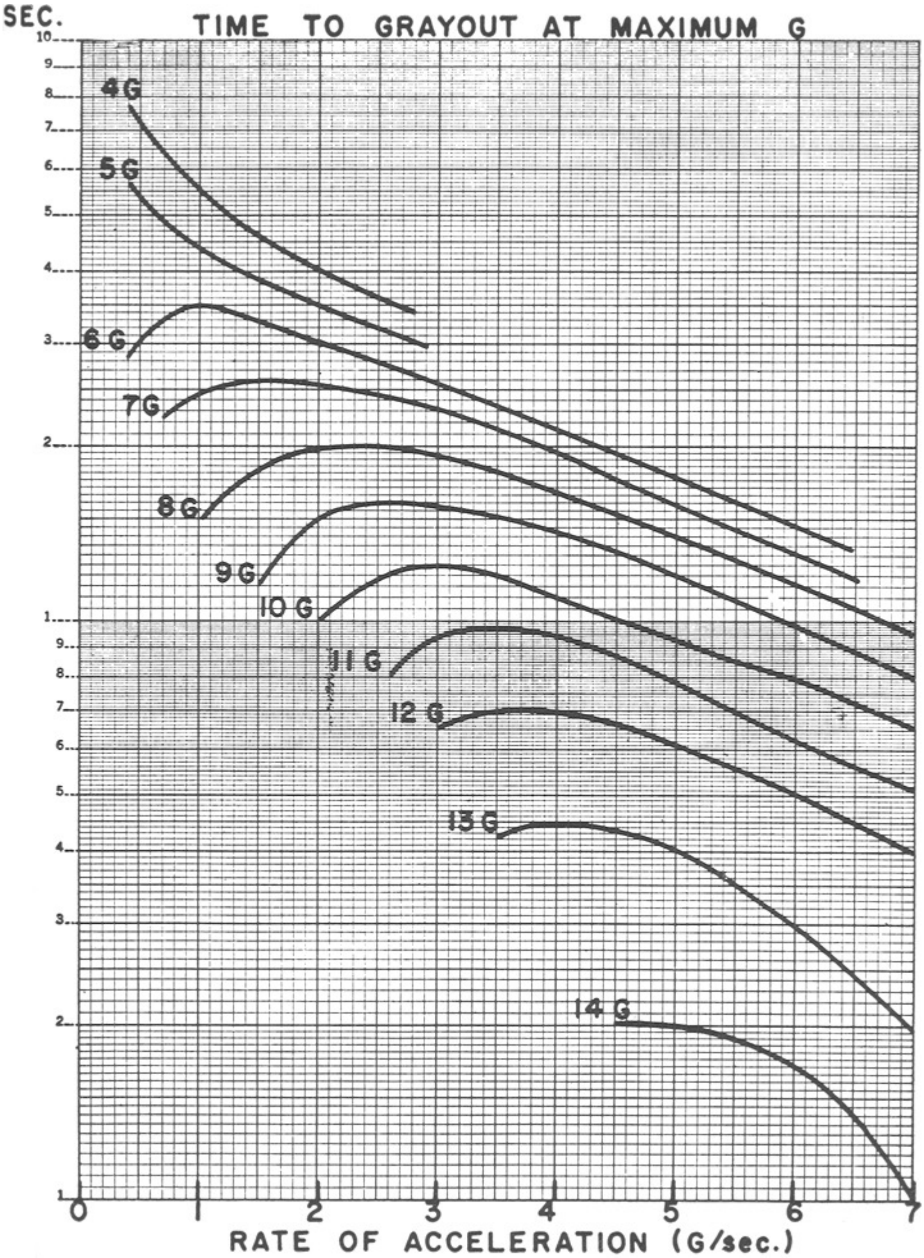

Fig. 6. Nomogram relating acceleration rate to time to end point.

be necessary. However, data available from other laboratories up to the present time are in agreement with those presented here as illustrated in Figure 7, in which are shown the mean points and the extremes of the 1,000 determinations cited above[4] plotted in the same manner as the present data and superimposed upon the tolerance curve. All of these data fall within the area delineated by the solid-line "box" around the symbols marked "P." The symbols are placed at the mean value for each physiological end point. The top and the bottom lines of the "box" indicate the extremes of the range of g covered and the sides indicate the extremes of the tolerance times observed. The dashed lines running vertically through each symbol indicate the average value with respect to g level and time for each end point throughout the experimental range covered. The dashed lines extend slightly below the bottom of the "box" to indicate that some points fall below 3.5 g, since in the original analysis the authors treat all data at 3.5 g and below as a single group.

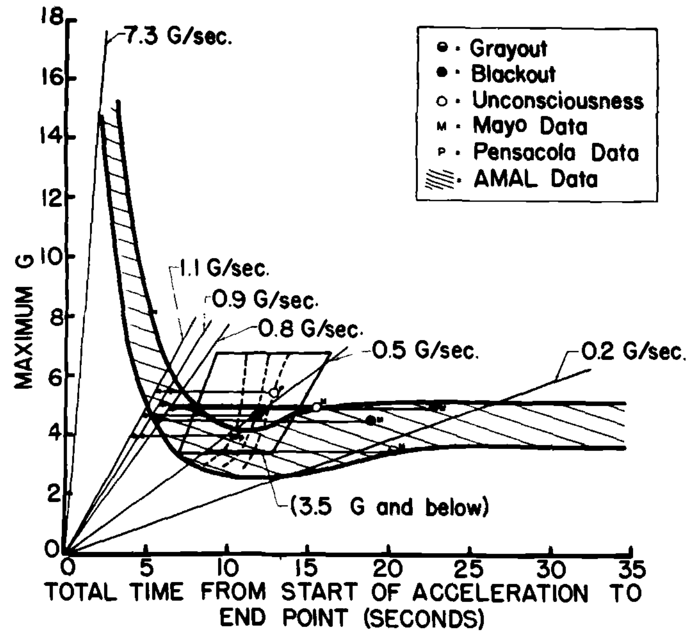

Fig. 7. Comparison of data from various laboratories.

Since the Pensacola centrifuge is limited in range of acceleration rates possible, only rates of 0.8 to 1.0 g per second were employed and all experimental end points fell close together with respect to the total curve, although taken by themselves, the range of variation in both g intensity and time at maximum g appear to be large. Actually, all these experiments fall in the most variable part of the tolerance curve where differences in time of onset and efficiency of the cardiovascular reflexes may be expected to be greatest. The Mayo Clinic centrifuge data are also plotted on this chart from published data[8] typical of the findings in that laboratory. It is seen that they, too, conform to the general pattern. In Figure 8 are shown data from the Wright-Patterson Air Force Base centrifuge studies.[10] In this chart, only time at maximum is compared since data on the time required to reach maximum *g* are not available at this time. The Wright-Patterson curve represents an average value for all symptoms and is shown compared with time at maximum to grayout and to unconsciousness as determined in the Aviation Medical Acceleration Laboratory studies. Again it is seen that all data are in agreement within the range common to both instruments. In view of these facts, it would appear that any changes brought about by additional data will be of a minor nature, tending to fix the range of variability rather than to displace the curve significantly.

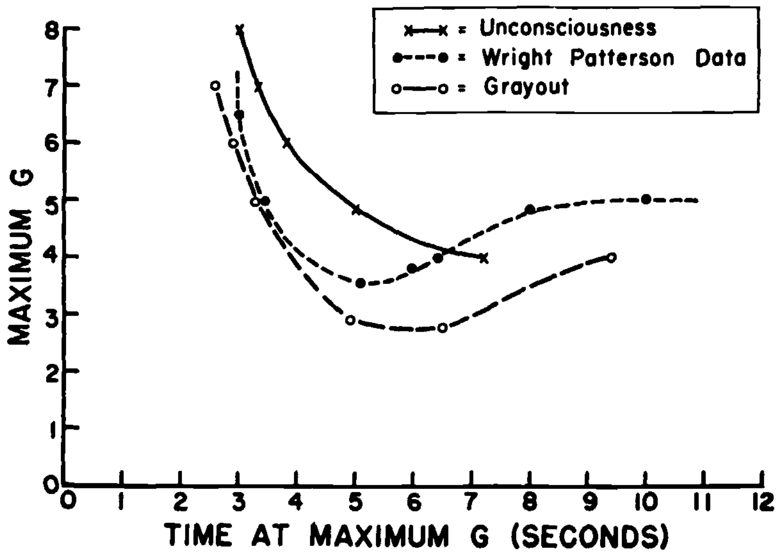

Fig. 8. Comparison of data from the Aviation Medical Acceleration Laboratory and Wright-Patterson Air Force Base.

DISCUSSION

The type of tolerance curve presented here provides a reference standard for studies of protection devices and measures throughout a wide range of *g* levels. It may be used as a basis for animal studies which may be pursued more rigorously than is feasible with human subjects. In this respect, the establishment of a tolerance curve for primates other than man, *e.g.*, the chimpanzee, would provide a basis for determining whether or not these animals are suitable substitutes for human subjects. For instance, a finding of a G-tolerance no greater than 1-2 *g* higher than that of humans or perhaps of a 10-20 per cent longer tolerance time, would indicate suitability for such substitution. A comparison of the arterial blood pressure fall in the chimpanzee, and human tolerance with time of exposure to accelerative stress (Fig. 9, composite of Figs. 2 and 3) reveals that the lowest pressure level occurs at the same time as the minimum in the tolerance curve, indicating that the tolerance pattern of the chimpanzee may well be quite similar to that of man. A complete tolerance curve would provide a means of relating animal experimentation to human experience more directly than by arbitrarily assumed safety factors of 2-3 fold magnitude of stimulus intensity employed heretofore.[2]

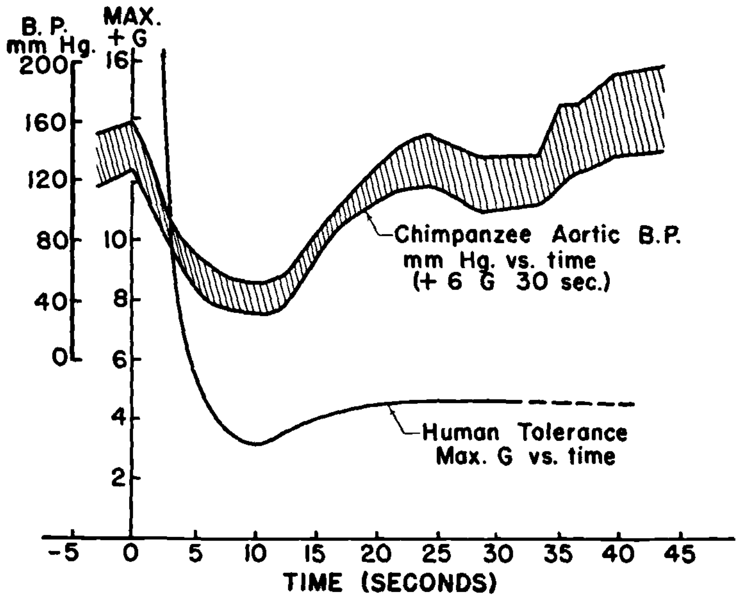

Fig. 9. Comparison of aortic blood pressure (chimpanzee) variations with time at 6 *g* and human tolerance variations with maximum *g* and time.

SUMMARY

A method of analysis adapted to the use of data covering a wide range of acceleration rates is described. This method is used in the analysis of the accumulated data available at the Aviation Medical Acceleration Laboratory on tolerance to a wide range of levels of positive *g* resulting in grayout, blackout and unconsciousness in unprotected humans. The data are plotted as a strength-duration curve of maximum *g* *vs.* total time of exposure to *g*. The curve is found to conform to the usual physiological patterns except in the range of low *g* for exposure times longer than 6 seconds, in which area cardiovascular reflexes become effective in increasing *g* tolerance.

Comparisons with similar data from other laboratories indicate that good agreement is obtained when the time required to reach maximum *g*, as well as time at maximum, is taken into consideration.

Because of the precision of the experimental procedure employed and the agreement obtained in areas where comparable independent data exist, it is concluded that in spite of the relatively small number of individual end points (forty), the tolerance curve as drawn here may serve as a valid standard of reference for protection studies and for animal studies employing similar patterns of acceleration.

A nomogram derived empirically from the experimental data is presented from which may be found the approximate tolerance time for various levels of g attained at various constant, linear rates of acceleration. This chart may serve as an instruction device and a guide in experimental design.

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Cost of Airline Passenger Meals

In their effort to attract and hold new business, airline operators vie with each other to provide tasty, attractive meals for passengers. This culinary spirit is probably not so keen in the United States as it is in other countries, where planes on epicurean flights at times go out of their way to provide time aloft for the eating of meals. Nevertheless, domestic scheduled airlines today are spending more money to feed their passengers than they spent not many years ago to fly them. The cost for complimentary meal service on scheduled airlines in 1954 was more than $22 million.—WILLIAM H. MEGONNELL and HOWARD W. CHAPMAN: *Public Health Reports*, 71:362, Apr. 1956.