HUMAN TOLERANCE TO ABRUPT DECELERATION IN WATER: AN ANALYSIS OF FREE FALLS FROM TWO BRIDGES

J.C. Lane*, M.F. Penfold, J. Laing**, J.B. Bailey & J.I. Tonge***

Limits to the systematic study of human tolerance to acceleration, as to other harmful environments, are set by possible experimental procedures. Animal and cadaver experiments have been valuable but do not completely reproduce live human response, while volunteer human exposure must stop well short of irreversible damage.

Epidemiology based on natural events has helped to fill in the gaps -- as in de Haven's original analysis of survived falls and more recent collections described by Snyder (1). These cases represent extreme values, for only a few subjects are known to have survived, and such values will necessarily have wide confidence limits. By analogy with toxicology, a useful measure of tolerance to a class of acceleration would be the LD_{50}, the dose at which the mortality is 50%.

Naturally occurring falls of known heights can provide such data, when survived as well as fatal falls have been recorded. It should be possible to fix a data point for each height on a dosage mortality curve with impact velocity or height corresponding to dosage.

Impacts with water sometimes fulfil the requirements for suitable records of a series of falls. Such a series from the Golden Gate Bridge in San Francisco, included in other data of Snyder's (2), appears to yield 97% mortality for a drop of about 240 ft (73 m).

The records of falls from two other bridges, the Sydney Harbour Bridge and the Story Bridge in Brisbane, Queensland, provide additional sources of information as to mortality for a given drop.

SYDNEY HARBOUR BRIDGE

The bridge has a single span (neglecting approaches) of 503 m, the central point of the decking being 58.7 m above mean sea level. The deck describes a gentle curve, convex upwards, and the lowest point of the footway which is above water is about 54.3 m. The mean height above m.s.l. is thus 56.5 m.

Some 45 persons fell or jumped from the bridges within two years of its opening, in 1932. Erection of a safety fence on the pedestrian footways was started in January 1934 and during the period of its construction special guards were appointed to patrol the bridge. However, five more people made successful suicidal jumps. After the safety fence was completed falls from the bridge became uncommon -- evidently the

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* Director of Aviation Medicine, Dept. of Civil Aviation, Australia.
** Director, Division of Forensic Medicine, N.S.W. Dept. of Public Health.
*** Director, Institute of Forensic Science, Queensland.

fence was an effective countermeasure. Up to December, 1963, ninety people had fallen from the bridge and its approaches, 69 into water (Table 1). Of these, 60 falls were fatal, a mortality rate of 87%.

SOURCES OF MATERIAL

To collect data on these falls, police reports, coroner's records, post-mortem records and newspaper files were consulted (3). At the time concerned, more than 30 years ago, it was the practice of the coroner not to order post-mortem examinations unless there were "suspicious circumstances", so from the 60 fatal falls only 15 post-mortems were carried out. Another 30 cases had records of external injuries, and for the remainder no information as to their injuries is available. The non-fatal falls were followed up through hospital records, but of the nine cases only four hospital records were traced.

Fatal falls with full post-mortems. There were 15 of these (13 males, 2 females). There was a definite pattern of injury which included bruising of the skin in various parts of the body (probably indicating the body orientation on impact) bruising and superficial tearing of the lungs, rupture of the liver (this was the most common injury) and in some cases tearing of the heart and great vessels. Fractured bones other than the ribs were rare. The main post-mortem findings are summarised in Table 2.

It is noteworthy that there was no record of skull fracture, which was common in cases of falls to a solid surface -- in 10 of the 15 falls from the bridge on to concrete.

Fatal falls with only a record of external injuries. There were 33 such cases, of whom 9 were females. In accordance with the then practice, full post-mortems were not required when it was apparent that the victim committed suicide. However these records are of some value since they show small items such as "bleeding from nose", which might not have been included in a full report.

Bruises over the body were noted in almost all cases. The other recurrent observations were fractured ribs, and froth at mouth and nose, in some cases blood-stained. This raises the question that perhaps death was, in some cases, due to drowning and not to the impact injuries sustained (Table 3).

Fatal falls with no information as to injuries. There were 11 falls, in which two of the victims were females, where no information as to injuries is available.

Non-fatal falls. There have been nine falls which individuals survived; of these three were female. There was also a case of a 44 year old male who died in hospital an hour and a half after he made the fall (this is reported as a fatal fall). Of these

Table 1. Falls into water from Sydney Harbour Bridge

	during construction	opening of bridge to completion of fence (2 years)	completion of fence to Dec. 1963 (approx. 40 years)	total
fatal	2	47	11	60
non-fatal	1	4	4	9
total	3	51	15	69

Table 2. Internal injuries in victims on whom full post-mortems were performed — 15 cases

injury	no of cases
ruptured liver	11
blast injury of lungs	9
ruptured heart or great vessels	7
brain haemorrhage	5
ruptured spleen	5
renal haemorrhage	1

Table 3. Injuries and appearances revealed by external inspection — 33 cases plus 15 from Table 1

injury or appearance	no. of cases
bruising	28
broken ribs	23
froth, not bloodstained, at mouth or nose	16
"congested eyes"	7
froth, blood-stained	5
bleeding from nose and mouth	4
"broken bones"	4
bleeding from ear	3
torn perineum	2

nine cases, hospital records of four have been located. Newspaper stories contained accounts of injuries in the remainder of the cases.

FACTORS INFLUENCING SURVIVAL

Impact Velocity. The deceleration, and consequently the inertia force on vital body structures, depends on the velocity of the body at impact and the time it takes for the body to come to a rest. Terminal velocity is usually regarded as being reached after 12 seconds of fall, when the air drag equals the weight of the body. However, it is unlikely that over a fall of 57 m terminal velocity would have been reached. In this series height is not a variable factor since all falls were through substantially the same height, and the effect of tide ($\pm$ 1.07m) is negligible.

Interpolation in the curve of drop height versus impact velocity given by Snyder (1) yields an impact velocity of 30.5 m/s for a drop of 57 m at sea level.

Attitude on Impact. It is reasonable to suppose that entering the water in a clean dive or feet first, ensuring that the body penetrates further into the water and decelerates over a greater distance than in case of a transverse impact, would improve the chance of survival. Snyder (2) refers to regular diving by professionals from heights of 30.5 m and 41.1 m. Most of his 50 survived free falls, with velocities exceeding 16.8 m/s were in the feet first or head first attitudes. The fact that such a falling body will impact the water with a greater velocity due to less air drag (provided the head or feet first attitude is maintained) is evidently of less consequence than the difference in deceleration distance. In this series information is available as to attitude at impact in only a few cases.

Physical Condition. The physical condition of the subject at the time of the fall might influence the chance of survival; no information is available in this series.

Sex. The small difference in mortality between males and females, is not significant: 45 males were killed in 51 falls (88%): 15 females in 18 falls (83%).

Age. The ages of fatally and non-fatally injured persons whose ages are known are shown in Table 4.

The distribution suggests that the elderly are under-represented in the non-fatal group, i.e. that is there may be an association between age and non-survival. If the age distribution be divided between ages 49 and 50, the 49 and below group has a mortality of 84% and the 50 and above group 100%. Despite the absence of individuals over 50 in the non-fatal class, this association might well occur by chance (the exact probability is 0.2).

Environment. The prospects for prompt rescue are particularly good. The waterway beneath the bridge carries considerable traffic, with consequent good chance of detection and quick recovery. A boatshed maintained by the police is located at the base of the southern pylon and victims can be reached in a matter of minutes. The water temperature is 12.2°C in July and 23.3°C in January, with an annual mean of 18.3°C.

The harbour is naturally protected and the waters under the bridge are usually calm. An estimate of the size of the waves can be obtained from the empirical formula, $h = 1.5\sqrt{d}$, where h is the height of waves in feet and d is the fetch in nautical miles. This formula yields a wave height of about 2.1 ft (0.6 m) under the bridge, a condition under which even poor swimmers can remain afloat if they are conscious.

The victim's ability to fall vertically may also be important and the wind velocities under the bridge may be less than the 5 to 30 knots (2.7 to 15.2 m/s) quoted by Snyder (2) for the Golden Gate Bridge.

STORY BRIDGE, BRISBANE RIVER

The bridge crosses a sheltered reach of the Brisbane River. The span is 466 m and at the centre of the bridge the footway is 37 m above the mean tide level. Each pedestrian crossing is 3 m wide and is bordered by a 1.9 m high safety fence. The bridge runs in a north-south direction, the north end jutting directly off a steep rocky slope.

Bridge construction began in July, 1935, and was completed in November, 1939. During this period there were three accidental falls, two into water and one on to land.

SOURCES OF MATERIAL

The survey period was 23 November, 1937, to 31 December, 1966. Data regarding the 40 recorded falls were extracted from post-mortem reports of the Institute of Forensic Pathology, hospital records, police records, newspapers and from meteorological records (4).

Every effort was made to secure a 100% sample. Most known survivors experienced difficulty in reaching the shore unaided, so that it is unlikely that a person who survived a fall from the bridge into the river would have reached the shore unnoticed. The length and tortuous course of the Brisbane River make it improbable that any bodies have been lost completely by being washed out to sea.

Falls into water - fatal. Of the 20 falls into water, 12 or 60% were fatal. In two of the 12 cases the survival times are not known. Death was immediate in two cases and in another six cases death occurred within 10 minutes of impact. In the remaining two cases death occurred after periods of 30 minutes and $4\frac{1}{2}$ hours, respectively.

Attitude at impact was available in only one of the 12 cases. This impact was transverse but it could not be determined if the subject struck the water in a prone or supine position. This subject survived for a period of four and a half hours.

Alcohol was detected in only two of the 12 cases. In one the blood alcohol level was 0.08% and in the other 0.15%. In both, death occurred within five minutes of the subject striking the water.

Drowning was considered to be the major immediate cause of death in seven cases but in only one of these was death due to drowning alone. In six, chest and abdominal injuries were major contributing factors but were not in themselves sufficient to have caused immediate death.

Crush injury to the chest was the major immediate cause of death in three (25%) cases. In the remaining two cases, the major immediate cause of death was ruptured aorta in one and gross haemorrhage into both pleural cavities in the other.

Head injuries occurred in six of the fatal cases: five received superficial head injuries, two sustained an injury to the eye and four had intra-cranial haemorrhage (extradural haemorrhage 1, sub-dural haemorrhage 1, intra-cerebral haemorrhage 2). There was no record of skull fracture.

Fractures of the ribs occurred in eight. There was also one case with a crush injury to a thoracic vertebra and one with a fractured pelvis. Two sustained fractured femora.

Superficial wounds of the chest were present in three and there was evidence of lung injury in five. One subject sustained a rupture of the heart and in another the subject had a rupture of the aorta. Haemothorax occurred in 11 of the 12 cases and mediastinal haemorrhage occurred in three.

The most common injury was moderately severe laceration of the liver which occurred in seven cases, and of the spleen in five. Contusion of the genitalia occurred in three cases. There were also single cases of retroperitoneal haemorrhage, laceration of a kidney, bladder rupture, and superficial injury to the abdomen. Superficial injuries to the lower limbs occurred in two. There were no skull fractures.

Falls into water - non-fatal. There were eight survivors of falls into water. Injuries sustained are shown in Table 5.

The attitude at impact was positively known in only five of the eight non-fatal falls into water. Of these five cases, three fell feet first into the water. Two sustained stiff buttock muscles and a bruised shoulder, respectively; one had no injuries.

Falls onto land - fatal. All of the 20 falls on to land were fatal and involved falls varying in height from 26 to 34 m. Of the 20 cases, 16 struck a concrete or bitumen surface. Death occurred instantly in 16 cases, the remaining four surviving for a period of hours.

The most common major immediate causes of death were laceration of the brain stem and crush injuries to the head (five cases). In three cases where death was due to laceration of the heart and three cases in which the major immediate cause of death was stated to be multiple injuries. There were also two cases of brain injury and one case of acute intrathoracic haemorrhage.

In comparison with injuries sustained in fatal falls into water, fatal falls on to land not surprisingly resulted in more extensive and usually more severe superficial injuries. In most cases there were multiple bone fractures of which the ribs, limbs, skull and pelvis were most commonly involved. Chest injuries were of a wider distribution and were more severe. Abdominal injuries appeared to be relatively minor -- except for superficial lacerations to the liver, kidney and spleen -- in comparison with the other injuries sustained.

FACTORS INFLUENCING SURVIVAL

Environment. The northern bank is well populated especially during the daylight hours. A cross-river ferry service operates less than 370 m upstream and another ferry service passes under the bridge every half hour. Wharves are situated along the northern bank of the river and on a number of occasions wharf labourers and crewmen from ships berthed at these wharves have been instrumental in rescuing suicides. The southern bank has a residential area on the upstream side and a large ship-building yard downstream of the bridge.

Details of the wind velocity and direction for the appropriate time of day were collected for each of the cases. Maximum wind velocity recorded at the time of a particular jump was 24 m/s.

The water temperature is 16°C in July and is 25.6°C in January, with an annual mean of 21°C.

The wave height beneath the bridge rarely exceeds 0.3 m from trough to crest (even with a strong wind blowing against the current).

Impact Velocity. Interpolation in the curve of drop height versus impact velocity yields an impact velocity of 24.4 m/s for a drop of 38 m at sea level and an impact velocity of 21.3 m/s for a drop of 34 m at sea level.

Sex, There were only two females in the 34 cases surveyed. Both were killed, one from a fall into water and one on to solid surface.

Age. As in Sydney there is a suggestive but non-significant relation between age and mortality.

VELOCITY AND MORTALITY

The numerical results of the three collections can now be brought together. Ideally the synthesis should be made by several classes of impact attitude, but insufficient information is available for the Sydney Harbour and Story series. It might be argued that, in different samples, the distribution of attitudes would be similar. This analysis is therefore based on random attitude at impact.

The suggestion of death from drowning, associated with non-fatal injuries, occurs in both the Sydney Harbour and Story series, so that a term corresponding to "natural mortality" is perhaps called for in estimating the curve. Evidently circumstances favoured a low drowning mortality in the Sydney Harbour and Story series, but were much less favourable at the Golden Gate. Because of this variation and since no good estimate of drowning mortality is available, it has been neglected.

From the data of Table 7, a probit has been computed yielding the dosage mortality curve of Fig. 1. LD_{50} is 24.8 m/s. corresponding to a drop of 33.5 m.

This curve must be regarded as a first approximation, which would be improved by additional data points, particularly for heights of drop between 20 m and 33 m.

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Table 4. Age distribution

age	fatal	non-fatal
– 20	2	1
21 – 30	10	1
31 – 40	10	2
41 – 50	14	3
51 – 60	5	
61 – 70	5	
	46	7

Table 5. Injuries to survivors

	no. of injuries
superficial chest injury	3
superficial head injury	2
injury to lungs	1
superficial abdominal injury	1
fractured pelvis	1
superficial limb injury	1

Table 6. Age distribution

age	fatal	non-fatal
– 20	1	1
21 – 30	1	3
31 – 40	2	1
41 – 50		2
51 – 60	7	1
61 – 70	1	
	12	8

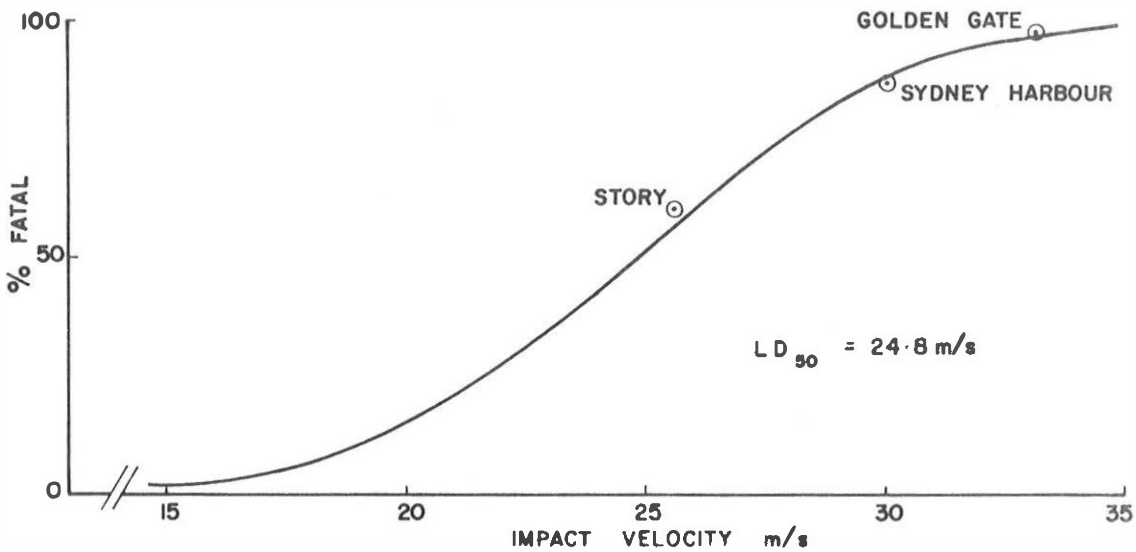

Fig. 1 Relation of velocity to mortality for random impact attitude.
The equation of the probit is $Y = -.399 + .216x$.

Table 7. Mortality for three bridges

	height. m	velocity, m/s	falls	fatal falls	mortality. %
Golden Gate	73	33.2	172	167	97.2
Sydney Harbour	57	30.5	69	60	87
Story	38	25.6	20	12	60

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