HEAD ACCELERATION TOLERANCE DERIVED FROM
FALLS INTO WATER

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1. INTRODUCTION

It is generally impossible, in accidents which involve head impact, to reconstruct the precise loading and acceleration to which the head is subjected. For this reason the study of water impact offers a useful source of additional data, since although the number of documented cases involving intracranial injury is small, it is possible to estimate the acceleration time history of the head on impact.

The purpose of this paper is to present data from earlier studies of falls into water, in a form which shows how the probability of brain damage is related to the peak acceleration and the head injury criterion.

1.1 Special features of water impact data

Two important features distinguish a level water surface from other obstacles against which the head may impact.

(a) *The distributed nature of the applied load*. The braking force of the water builds up rapidly to reach a maximum at an immersion depth of around 10 mm; the wetted surface area of the head is then already about 60 cm^2.

(b) *The absence of tangential impact forces*. Unlike the typical solid-surface impact, vertical impact of the head on a level water surface produces no significant tangential loading.

Because of these special features, water impact is relatively simple to analyse. Penetrating injuries, for example, are not seen. Our hypothesis in this paper is that brain damage can be related, in such impacts, to the vertical-acceleration time history of the head.

1.2 Outline of the approach adopted

Data on the incidence of brain damage in falls into water is taken from three published investigations (Section 2). The inferred probability (p), that brain damage will result from any given head impact on the water surface, is then plotted against two measures of exposure: the *peak acceleration* (G_{max}) and the *head injury criterion* (HIC).

The evaluation of these quantities relies on a hydrodynamic model of the water entry process which is described in detail elsewhere (Morfey 1986). The head is modelled as a rigid ellipsoid, whose impact velocity is calculated from the known height of fall. Section 3 explains how p, G_{max}

and HIC are derived; the final results are presented and discussed in section 4.

2. SOURCES OF MATERIAL

Three sources of fatalities caused by falls into water have been documented in sufficient detail, with information on intracranial damage, to be useful in the present study.

(a) *San Francisco - Golden Gate Bridge*. Snyder and Snow (1967) collected post-mortem records on 169 fatal falls (117M, 52F) from this bridge, covering the period 1937-1966. The mortality rate for all known falls up to August 1966 was 0.99 (2 survivors in 305 falls). The victims in their study included 10 under age 25 (14 less than 55 kg); the median body weight was about 70 kg (body weight is important in falls from heights of around 40 m or more, because aerodynamic drag affects the impact velocity).

Injuries included 62 cases of brain damage - typically subarachnoid haemorrhage - and 40 cases of skull fracture. This distribution is broadly confirmed - though with fewer skull fractures - in a more recent study by Lukas et al (1981) based on 100 fatalities.

(b) *Sydney - Sydney Harbour Bridge*. Lane, Penfold et al (1973) collected records on the 60 fatalities (45M, 15F) between 1930 and 1963. During this period there were 69 recorded falls into water from the bridge. The victims included 2 under age 21.

Full post-mortem examinations were performed on only 15 out of the 60 cases. These revealed 5 instances of brain haemorrhage, and no skull fractures.

(c) *Brisbane - Story River Bridge*. In the same paper (1973), Lane, Penfold et al presented data on 12 fatalities (11M, 1F) between 1937 and 1966. These represent all the known fatalities; during the same period a total of 20 falls into the water were recorded. One victim was under 21. Injuries found at post-mortem included 4 cases of intracranial haemorrhage. There were no skull fractures.

For each of the 3 series, the range of heights fallen is known within narrow limits. The impact velocity has been calculated as described in the Appendix, and results are summarised in Table 1. Velocities on impact range from around 24 m/s (Story Bridge) to around 32 m/s (Golden Gate), assuming a transverse body attitude during fall.

It is noteworthy that in none of the 3 series is there any record of brain damage among *survivors*. A subsequent detailed study of the 14 known survivors in 92 falls (1930-1982), from Sydney Harbour Bridge into water, underlines this point (Harvey and Solomons, 1983): they state "*there were no skull fractures, and no evidence of intracranial haemorrhage in any of the survivors.*"

3. METHOD OF ANALYSIS

Three main problems have to be addressed in this study. They are:

(1) estimation of the likelihood of brain damage for direct head impacts,in each of the three series of falls described in section 2;

(2) estimation of the acceleration time history experienced by the head in such impacts;

and finally, as a first step in solving problem (2),

(3) modelling of the head by an equivalent rigid body.

3.1 Likelihood of brain damage, in direct head impacts on a water surface

The objective here is to obtain the probability (p) of brain damage, as a function of vertical impact velocity. We can estimate p from the data in section (2) as follows.

(a) Subject to possible later correction (see section 4), we assume $p = 1$ for the Golden Gate set of falls.

(b) A certain proportion (r) of all falls is assumed to involve direct head impact. In the remaining falls, e.g. those in a feet-first attitude, the head will be shielded and it is assumed that no brain damage occurs (at least at the impact velocities of up to 35 m/s encountered in this study).

(c) It follows from the Golden Gate bridge data that

$$r = 0.99\ (62/169) = 0.363.$$

The same value is assumed to apply to the other two sets of data. Thus the expected number of direct head impacts is rN_{tot}, where N_{tot} is the total number of falls (fatal or non-fatal) in the series.

(d) Finally, p is deduced from the number of cases (N) of brain damage as

$$p = N/rN_{tot} \qquad \text{(Story River)}$$

or

$$p = 4N/rN_{tot} \qquad \text{(Sydney Harbour, 25\% post mortem).}$$

Table 2 summarizes the results of this calculation. Two points may be noted. First, both series show p values significantly lower than was assumed for the Golden Gate data ($p = 1$). Applying a chi-squared test in turn to the Story River/Golden Gate and Sydney Harbour/Golden Gate pairs of data shows the differences to be statistically significant at the 5 percent level. Second, despite the uncertainty associated with the small numbers, the trend between the Story River and Sydney Harbour results is in the expected direction.

3.2 Quantification of head impact exposure

By modelling the head as a rigid ellipsoid in free fall, with one of its axes vertical, a theoretical estimate can be made of the acceleration time history of the centre of mass on impact. Details of the theory, which is based on established methods of fluid dynamics, are given elsewhere (Morfey 1986). An important feature of the prediction is that the acceleration time history is determined solely by:

(a) The velocity of impact (U_o)
(b) The semi-axis of the ellipsoid, measured in the vertical direction (R)
(c) An aspect ratio parameter (β), defined below, which also accounts for the density of the ellipsoid relative to water.

The parameter β is defined as follows. The vertical semi-axis of the ellipsoid is denoted by R, and the radius of the equivalent-volume sphere by a. Then

$$\beta = (R/a)^{3/2}\sigma,$$

where σ is the ratio of the ellipsoid density to the water density.

The principal results of the ellipsoid water entry calculation are summarised in Figures 1-3. Figure 1 shows the normalised acceleration time history, for $\beta = 1$ (e.g. a sphere of relative density 1). Figures 2 and 3 show the values of peak acceleration and head injury criterion (HIC) respectively, as functions of β. Clearly there is a strong dependence on β; the question of which value is appropriate for simulating head impact is taken up in the next section.

3.3 Equivalent ellipsoid head model

Inertial properties of human heads have been measured by Beier et al (1977). They present data on the mass and moments of inertia of 21 heads, where the moments of inertia are referred to the principal axes (X', Y', Z') passing through the mass centre. Figure 4 illustrates the orientation of these axes.

From this data one can infer the density and dimensions of an ellipsoid having the same mass and moments of inertia as a particular head. Average values (and standard deviations) are listed in Table 3, for the 5 heads which were most nearly symmetrical about the mid-sagittal plane. The density is very close to 1 relative to water. The smallest semi-axis (and hence the impact direction giving the severest deceleration) is the the Y' = Y direction.

However, lateral water impacts (with the side of the body striking the water) will be shielded by the shoulder to some extent. For prediction purposes, we therefore choose a value of β based on impact in the ± X' direction (Figure 4) as representative of those real-life impacts responsible for brain damage in the falls being studied. (If data were available on the actual direction of impact in each case - which it is not, for the present data series - this crude assumption could be refined).

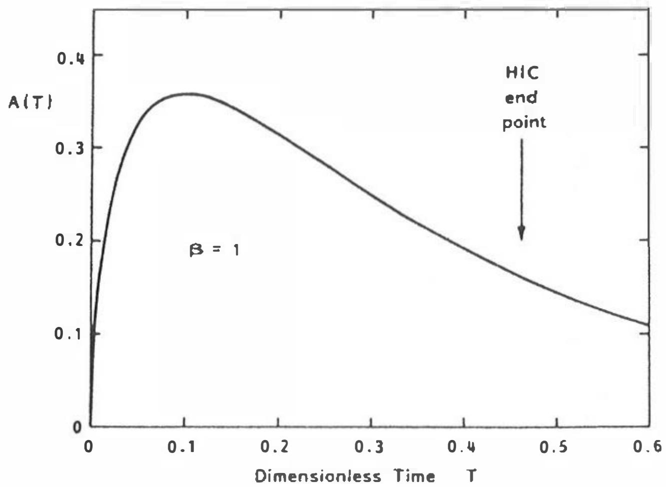

FIGURE 1. Predicted time history of the normalised acceleration A(T) on impact, for vertical water entry of a neutrally buoyant sphere (aspect ratio parameter = 1).

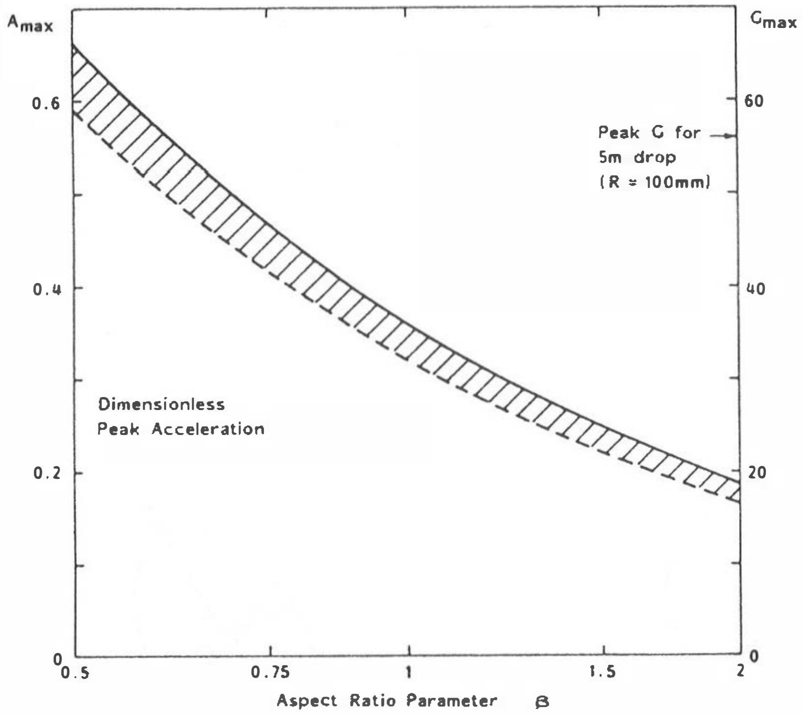

FIGURE 2. Dimensionless peak acceleration of an ellipsoid during vertical water entry, as a function of the aspect ratio parameter. The absolute acceleration is proportional to h_o/R. The solid and broken lines correspond to two theoretical models; the spread indicates the degree of uncertainty in the predicted accelerations.

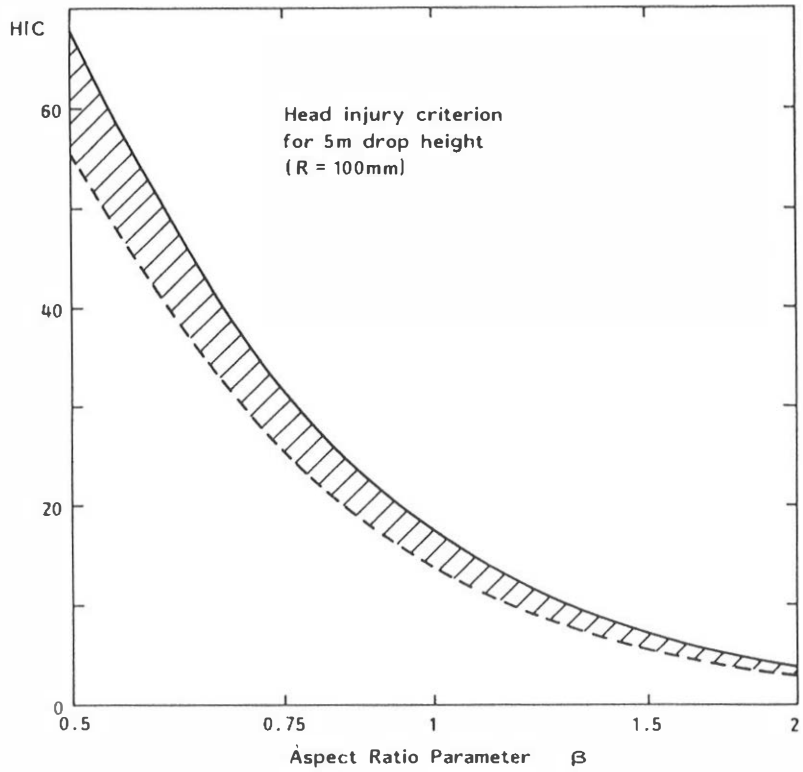

FIGURE 3. As Figure 2, but showing the head injury criterion predicted from the same model. Values for other drop heights and radii may be scaled from the curve by noting that HIC varies as $h_o^2/R^{1.5}$.

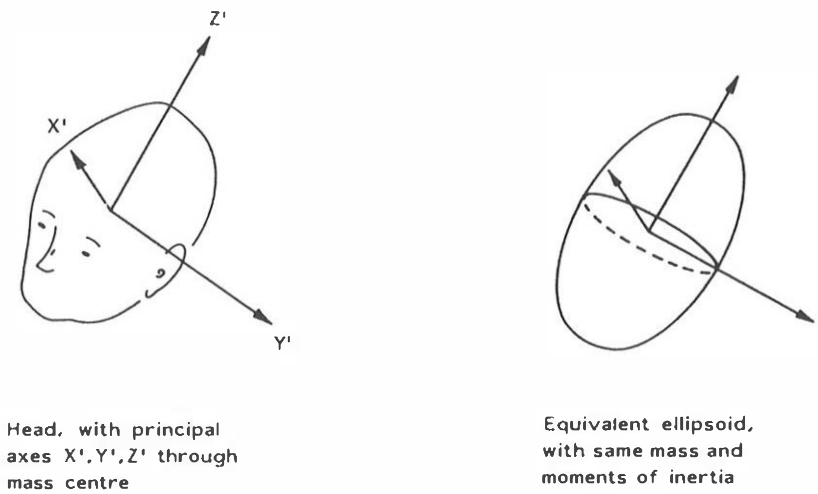

FIGURE 4. Sketch showing principal axes of head and equivalent ellipsoid.

The values chosen for use in section 4 are $\beta = 0.875$ and $R = 94$ mm. It follows from water impact theory (Morfey 1986) that the peak G value and the HIC value may be estimated as

$$G_{max} = bh_o \quad \text{and} \quad HIC = ch_o^2$$

where h_o ($= U_o^2/2g_o$) is the equivalent free-fall height under standard gravity (without air resistance). The constants (b,c) are found from Figures 2 and 3 as

$$b = 7.68 - 8.64 \; ; \quad c = 0.80 - 1.00 \qquad (h_o \text{ in metres}).$$

The ranges given above for b and c reflect uncertainties in the hydrodynamic modelling; they are included in all subsequent calculations.

4. RESULTS AND DISCUSSION

Figures 5 and 6 summarise the results of the calculations described in section 3. They show the probability (p) of intracranial damage occurring when the human head strikes a level water surface. The head orientation is not specified, but the implication is (for the cases discussed in section 2) that brain damage is associated with a transverse or lateral body attitude on impact.

In Figure 5, p is plotted against G_{max}, using logarithmic scales for $p/(1-p)$ and G_{max}. These scales facilitate interpolation, since data are expected to fall approximately on a straight line. Extrapolation to the G_{max} range predicted for the Golden Gate Bridge falls yields a predicted p value between 0.80 and 0.96: in other words there is a high probability of brain damage, in the range 32-35 m/s head impact velocity, which is consistent with the initial assumption of $p = 1$ for this series.

Similar remarks apply to Figure 6, where p is plotted against HIC. Whereas Figure 5 is limited to impacts of particular duration (of order 1-2 ms at the 0.5 G_{max} level), Figure 6 presents the same human tolerance data in what should be a generalised form, valid for a range of head acceleration curves.

4.1 Head acceleration tolerance prediction

The upper of the two lines which bracket the data, in either Figure 5 or Figure 6, may be used as a (somewhat conservative) predictor of intracranial damage caused by severe head accelerations. The equations are both of the form

$$p = \frac{1}{1+x}$$

where

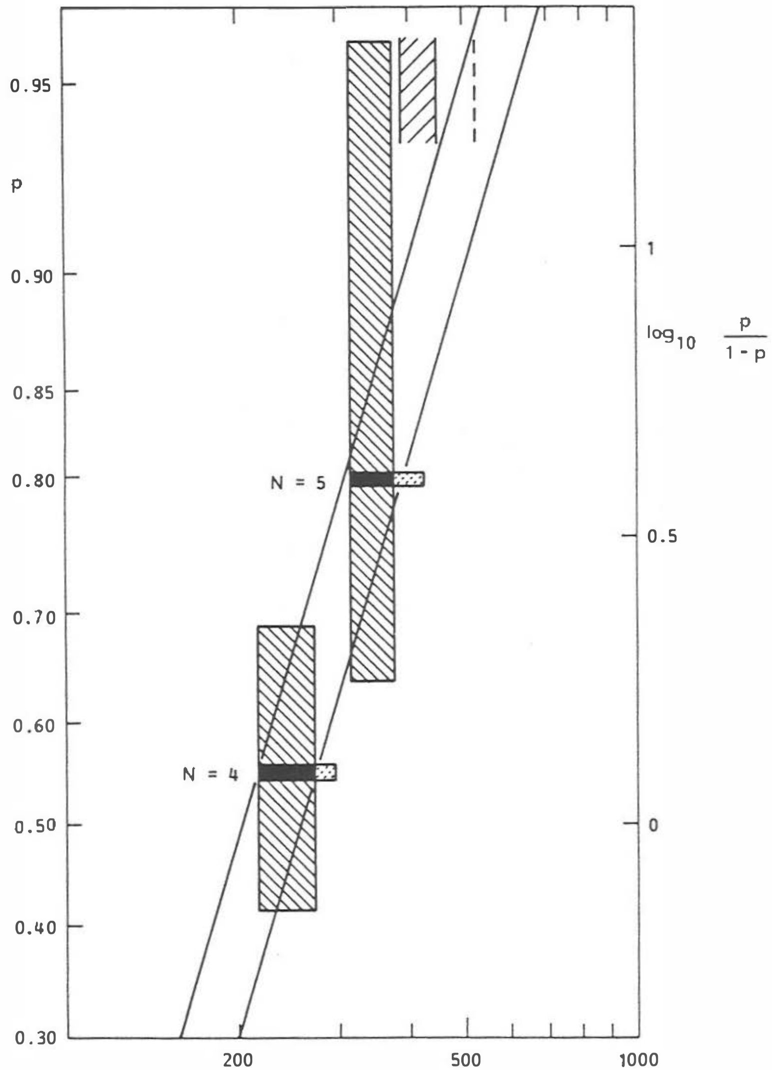

FIGURE 5.

Probability of intracranial injury in type (a) water impacts, derived from 3 series of falls from bridges. Solid bars indicate the peak G range predicted using Z = 110; extensions indicate higher G values predicted using Z = 180. Vertical range shows the effect of $\pm$ 1 change in N.

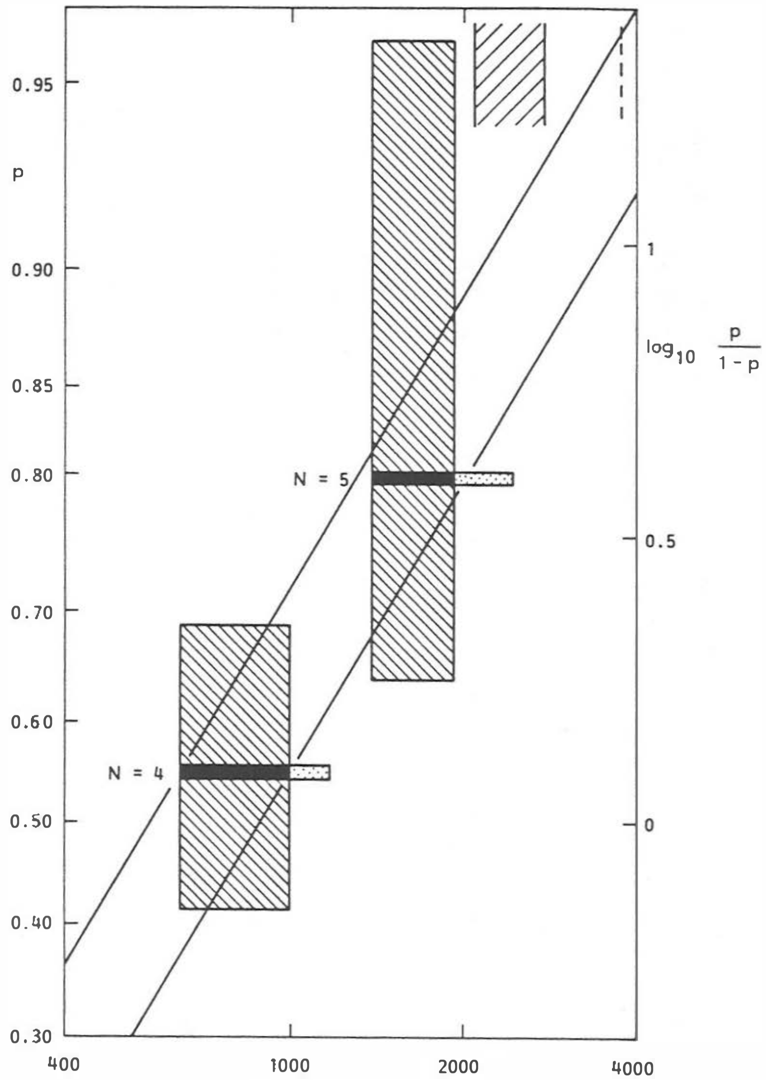

FIGURE 6.

As Figure 5, except that the horizontal scale is HIC. Data range and sensitivity are indicated as in Figure 5. Shown at the top of the figure (also in Figure 5) is the predicted HIC range for falls from the Golden Gate Bridge.

$$x = (205/G_{max})^{3.32} \qquad \text{(acceleration curve)}$$

or

$$x = (570/HIC)^{1.66} \qquad \text{(HIC curve).}$$

4.2 Breakdown of HIC for long-duration impacts

Although Figure 6 suggests that HIC values around 2000 will almost certainly cause brain damage, there is evidence of survival at even higher values when the impact is of relatively long duration. Snyder (1966) quotes an interesting and well-documented example which illustrates the point. A paratrooper fell through a height of 365 m into snow, landing flat on his back with the parachute unopened. He suffered only minor injuries. The fall would have reached almost terminal velocity. Assuming a Z value (see Appendix) of 150 kg/m^2 - which would correspond to a weight of 88.5 kg (including equipment) with C_DS = 0.57 m^2 (transverse attitude) - together with an air density (1.37 kg/m^3) and g value (9.821 m/s^2) appropriate to local conditions, we obtain 45.5 m/s for the impact velocity.

The stopping distance is estimated as 1.22 m (4 ft), this being the crater depth (3 1/2 ft) plus 1/2 ft for body deformation. Thus even on the most favourable basis, that is assuming a constant deceleration, the paratrooper survived 87 G for just over 50 ms, which implies an HIC around 4000.

Data such as this clearly point to limitations in the use of HIC as a damage predictor. Aside from the long duration, a favourable factor in the example cited may also have been the absence of head rotation on impact. Head rotation cannot be excluded as a cause of injury in the water impact cases studied, and further work is required to establish the likely damage mechanisms.

5. CONCLUSIONS

(1) Evidence from 3 series of falls into water supports the hypothesis that for heights of between 34 and 80 metres, two categories of water impact can be distinguished:

(a) Impacts in which the head strikes the water directly, in a manner liable to cause intracranial injury;

(b) Impacts in which the head is allowed to decelerate less abruptly, e.g. as in feet-first water entry.

According to this hypothesis, intracranial injury is limited to impacts of type (a).

(2) The extensive series of falls studied by Snyder and Snow (1967), totalling 169 fatalities, indicates that type (a) impacts make up about 36 per cent of all falls; and that such impacts are not survivable at 32 m/s impact velocity.

(3) Survival of head-first water impact by trained stunt divers has been documented up to 30.3 m/s impact velocity by Snyder (1965). By entering the water with the head in an optimal attitude and the neck held rigid, such divers avoid the rapid head deceleration and rotation that would otherwise occur. Such impacts therefore belong in category (b) above.

(4) By combining the evidence from the 3 series of bridge falls, we deduce that the incidence of intracranial injury in type (a) impacts diminishes from 100 per cent (at 32 m/s impact velocity) to about 80 per cent at 29 m/s, and to about 55 per cent at 24-25 m/s.

(5) The incidence of intracranial injury has been plotted against estimates of the peak G experienced by the head (Figure 5) and the head injury criterion (Figure 6). The resulting curves indicate that 50 per cent likelihood of intracranial injury occurs in a type (a) water impact at HIC = 570 (G_{max} = 205).

(6) The risk of head injury at longer exposure durations (around 50 ms) is not well described by the HIC index.

REFERENCES

BEIER, G., EWING, C.L. et al 1977 in Proceedings of 1977 International IRCOBI conference on impact trauma, W. Berlin, Sept 1977:218-277. Center of gravity and moments of inertia of human heads

HARVEY, P.M., and SOLOMONS, B.J. 1983 Medical Journal of Australia 1, 504-511. Survival after free falls of 59 metres into water from the Sydney Harbour Bridge, 1930-1982.

LANE, J.C., PENFOLD, M.F. et al 1973 in Proceedings of the International Conference on the Biokinetics of Impacts, Amsterdam, June 1973: 83-93. Human tolerance to abrupt deceleration in water: an analysis of free falls from two bridges.

LUKAS, G.M., HUTTON, J.E., LIM, R.C. and MATHEWSON, C. 1981 Journal of Trauma 21, 612-618. Injuries sustained from high velocity impact with water: An experience from the Golden Gate Bridge.

MORFEY, C.L. 1986 ISVR Memorandum No 653, University of Southampton, Institute of Sound and Vibration Research. Head accelerations caused by direct water impact: a study of tolerance criteria based on falls into water.

SHIFFMAN, M. and SPENCER, D.C. 1947 Quarterly of Applied Mathematics 5, 270-288. The flow of an ideal incompressible fluid about a lens.

SNYDER, R.G. 1965 Aerospace Medicine 36, 940-947. Human tolerance limits in water impact.

SNYDER, R.G. 1966 Military Medicine 131, 1290-1298. Terminal velocity impacts into snow.

SNYDER, R.G. and SNOW, C.C. 1967 Aerospace Medicine 38, 779-783. Fatal injuries resulting from extreme water impact.

APPENDIX: Calculation of velocity in free fall

The impact velocity is estimated in each case from the height fallen (h), the gravitational acceleration (g) and the air density (ρ_a), together with a parameter

$$Z = m/C_DS$$

which depends on the individual's body build and clothing as well as the body attitude. We treat Z as a constant during the fall, and use the values Z = (110,180) kg/m^2.

According to Snyder (1966), C_DS values can vary between 0.325 and 0.65 m^2. A value of 0.59 m^2 is chosen as typical of falls in a transverse (X axis vertical) or lateral (Y axis vertical) body attitude: with m = 64.9 kg (143 lb) as a typical body weight, we then obtain the lower value of Z = 110 kg/m^2. The higher value is the one used by Snyder (1965, 1966, 1971): it corresponds to C_DS = 0.437 m^2 and m = 78.6 kg (173 lb).

The equations used in the present study are:

(Terminal velocity) $U_\infty^2 = 2g'Z/\rho_a$ (ρ_a = air density)

(Effective gravity) $g' = g(1 - \rho_a/\rho_b)$ (ρ_b = body density, 1000 kg/m^3)

(Impact velocity) $$U_o = U_\infty \left[1 - \exp - \frac{2g'h}{U_\infty^2}\right]^{1/2}$$

Values of g and ρ_a for the 3 bridge locations are listed in Table 4, together with the resulting terminal velocities for the two Z values above.

TABLE 1. Heights and impact velocities for falls from three bridges

	Golden Gate	Sydney Harbour	Story River
Height fallen (m)	75.9-79.55	55.6-60.0	34.0-38.9
Impact velocity (m/s) Z = 110	31.6-32.1	28.5-29.3	23.6-24.9
Impact velocity (m/s) Z = 180	34.0-34.7	30.1-31.1	24.4-25.9

TABLE 2. Cases of intracranial injury in fatal water impact

	N	N_{tot}	% post-mortem	Estimated p
Sydney Harbour	5 (4-6)	69	25	.798 (.638-.958)
Story River	4 (3-5)	20	100	.551 (.413-.688)

TABLE 3. Inertial properties of human heads, expressed in terms of an equivalent ellipsoid (Beier et al, 1977)[a]

Mean density/(standard deviation) (kg/m^3)	Ellipsoid semi-axes/(s.d.) R_X, (mm)	R_Y, (mm)	R_Z, (mm)
979/(7)	94.3/(2.5)	87.6/(5.0)	129.9/(3.2)

[a]Based on the 5 specimens closest to lateral symmetry (serial numbers 7, 13, 14, 19, 20).

TABLE 4. Values used for aerodynamic drag calculation

	Grav.acc. $g\,(m/s^2)$	Air density $\rho_a\,(kg/m^3)$	Z (kg/m^2)	Terminal vel. $U_\infty\,(m/s)$
Golden Gate	9.800	1.231	110 - 180	41.8 - 53.5
Sydney Harbour	9.796	1.213	"	42.1 - 53.9
Story River	9.791	1.202	"	42.3 - 54.1

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