AN ASSESSMENT OF CRITERIA FOR THE PREDICTION OF CONTUSION INJURY UNDER NON-PENETRATING THORACIC IMPACT

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ABSTRACT

A study has been carried out to assess the effect on injury level of the parameters which characterise a non-penetrating thoracic impact. This study has used the dynamic finite element code DYNA2D[1] and the dynamic simulation code GENDYN[2]. Injury level has been calculated using a range of criteria. These criteria have included the maximum acceleration of the chest wall and Viano's Viscous Criterion[3] based on chest wall motion as well as criteria based more closely on the factors which actually produce the injury (such as the maximum rates of change of pressure (dP/dt_{max}) generated in the lung parenchyma during the impact).

The study has shown that acceleration of the outside of the chest wall is a very poor indicator of the expected injury level, bearing little or no relationship to the actual pressure conditions in the lung. Viscous Criterion based on internal motion of the chest wall has been shown to be a good criterion and the maximum chest wall internal velocity or acceleration also show good agreement with expected injury level. The best criteria are those which take account of dP/dt_{max} at all points in the lung. Injury indices based on these criteria are very difficult to determine experimentally but mathematical modelling can calculate their values without undue difficulty.

1. INTRODUCTION

Pulmonary contusion resulting from non-penetrating thoracic impact is an important injury mechanism in a wide variety of situations. These range from blast loading, through impacts of small projectiles on the thorax to impacts in car accidents. A number of criteria have been used to describe the likelihood or extent of contusion in a given type of impact but often their popularity relies more on the fact that they may be easy to measure than on a sound understanding of their physical basis.

At the 1988 IRCOBI Conference, the authors presented results from a study which had been performed by Frazer-Nash Consultancy Limited (FNC) for the Chemical Defence Establishment, MOD (PE), Porton Down, England[4]. This study had identified and explained the mechanisms which lead from thoracic impact to the generation of pulmonary contusion injuries. The paper described spring-mass-damper and dynamic finite element models which together enabled the pressure conditions in the lung to be determined and it was shown how these pressure conditions (particularly the rate of change of pressure, dP/dt) generated bursting pressures in the lung capillaries which caused failure of the capillary walls and hence flooding of the parenchyma with blood.

This work has now been extended by performing a parametric study to investigate how the level of injury depends on some of the parameters which characterise the impact (impactor mass and velocity, thorax "size" and lung density). The study has allowed an assessment to be made of the relative merits of a large number of possible injury criteria. In particular, each criterion has been assessed to see whether it correctly predicts the effect of changing the impact parameters and to determine whether it

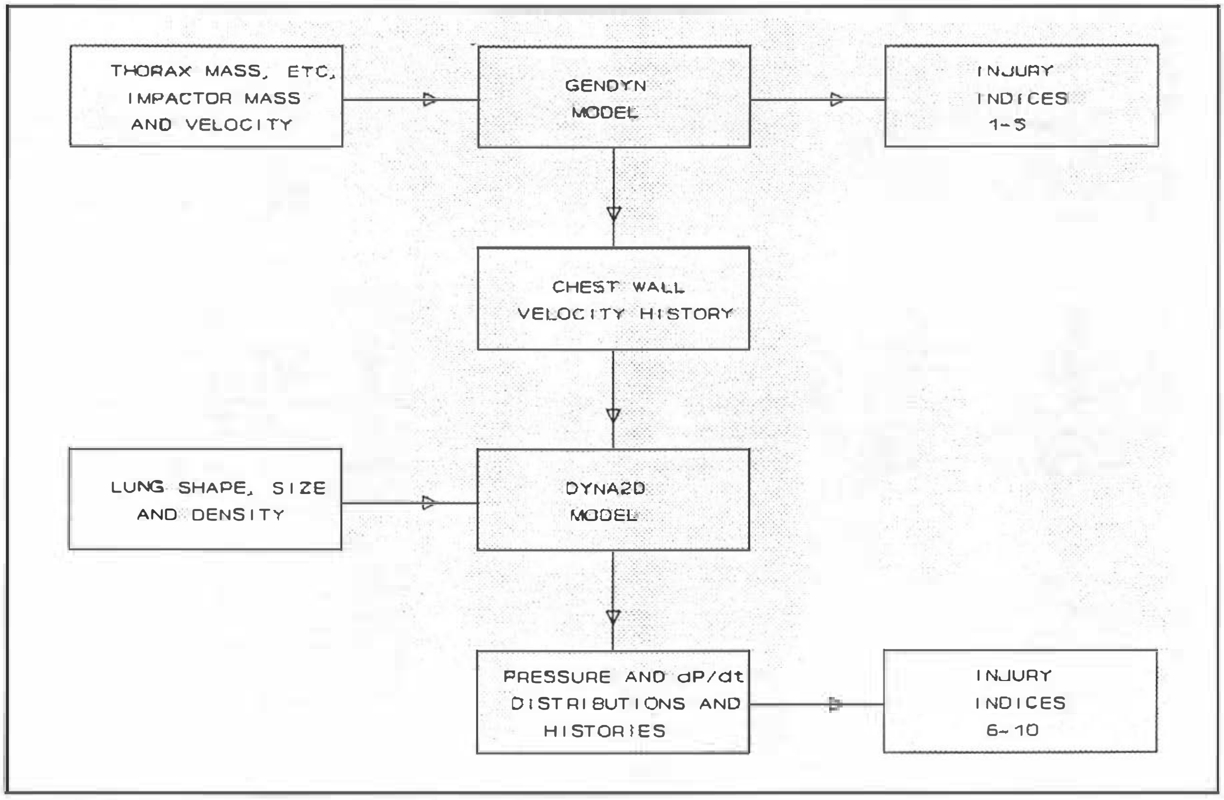

Figure 1: Parametric Study Schematic

reflects the actual conditions which cause contusion to occur.

2. METHOD

Figure 1 shows, in outline form, the method used for the parametric study.

The method involves four main steps:-

i) Determine model parameters from the properties of the thorax and the mass and velocity of the impactor.
ii) Determine the motion history of the inside of the chest cavity using the GENDYN spring-mass-damper model shown in Figure 2.
iii) Apply the motion history determined from the previous step to a DYNA2D lung section model as described in Reference 4 and hence determine pressure histories and distributions throughout the lung.
iv) From the results of steps (ii) and (iii), extract appropriate information to calculate the values of injury indices based on selected injury criteria (see Section 3).

The parametric study has considered the effects of changing each of the following parameters independently over appropriate ranges:-

- Impactor mass
- Impactor velocity
- Lung density
- Thorax "size"

It is assumed that all dimensions of the thorax remain in the same proportions and that density and modulus are independent of dimensions.

One set of models (ie. one GENDYN model and one DYNA2D model) has been generated for each value of each parameter.

3. INJURY CRITERIA

Ten possible criteria for determining the level of contusion in the lung have been identified. These may be split into two groups, namely

- Criteria based on chest wall motion. Indices based on these can be evaluated directly from the output of the GENDYN models.

- Criteria based on pressure conditions within the lung itself. Corresponding indices are determined from the output of the DYNA2D models.

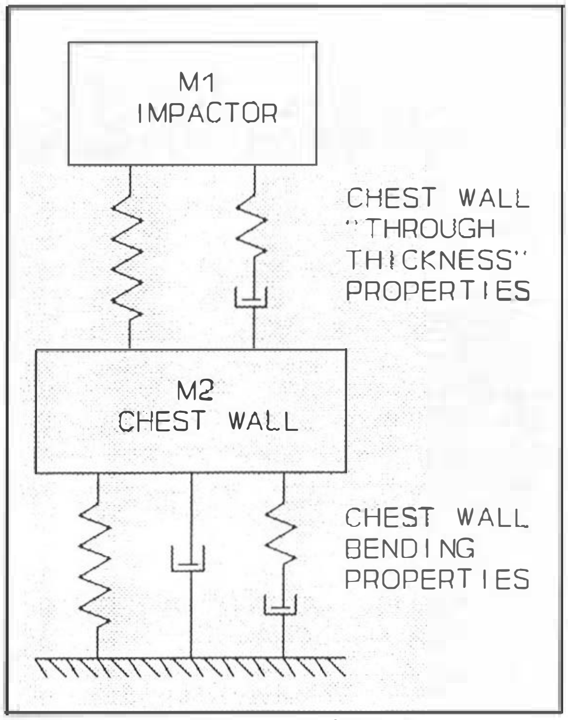

Figure 2: GENDYN Model

3.1 Injury Indices Determined From GENDYN Models

1. $VC_{max(int)}$. The maximum value of Viano's Viscous Criterion based on the motion of the inside of the chest cavity (ie. the motion of mass M_2 in Figure 2).

2. $VC_{max(ext)}$. The maximum value of Viano's Viscous Criterion based on the motion of the outside of the chest cavity (ie. the motion of mass M_1).

3. $V_{max(int)}$. The maximum velocity of the inside surface of the chest cavity (ie. maximum velocity of mass M_2).

4. $A_{max(int)}$. The maximum acceleration of the inside surface of the chest cavity (ie. maximum acceleration of mass M_2).

5. $A_{max(ext)}$. The maximum acceleration of the outside surface of the chest wall (ie. maximum acceleration of mass M_1).

A sixth criterion might, at first sight, appear to be worth including, namely $V_{max(ext)}$, the maximum external velocity of the chest wall. On closer examination, however, it can be seen that this will always be equal to the impact velocity. Impact velocity is one of the four parameters which has been varied during the study (see Section 2). As a result, all of the cases which considered the effects of changing one of the other three parameters used exactly the same value of impact velocity. However, very different levels of injury would be expected from these cases and so impact velocity may be immediately discounted as an injury criterion.

3.2 Injury Indices Determined From DYNA2D Models

6. P_{max}. The maximum pressure generated anywhere in the lung section.

7. dP/dt_{max}. The maximum value of dP/dt generated anywhere in the lung section.

8. $P_{max(point)}$. The maximum pressure achieved at a set position in the lung (eg. opposite the impact point).

9. $dP/dt_{max(point)}$. The maximum value of dP/dt achieved at a set position in the lung (eg. opposite the impact point).

10. $dP/dt_{max(mean)}$. dP/dt_{max} averaged over the entire lung section.

3.3 Discussion

Injury indices derived from the GENDYN models (Criteria 1-5) have the advantage that they can also be fairly readily determined from experiment. However they do not directly measure the conditions which actually cause the injury.

From Reference 4, it is known that capillary bursting and hence contusion are dependent on rate of change of pressure rather than on pressure itself. Extent of injury would therefore be expected to depend on the maximum level which dP/dt reached at each site in the lung.

$dP/dt_{max(mean)}$ considers maximum levels of dP/dt at all sites in the lung and takes account of spatial variations by performing an area average to give one number which characterises the overall conditions in the lung. Therefore, this index is considered to be the best indicator of the likely extent of injury and is taken as the standard against which the others are assessed.
However, $dP/dt_{max(mean)}$, in common with the other indices derived from the DYNA2D models (Criteria 6-10), is by no means simple to determine experimentally. Determining $P_{max(point)}$ and $dP/dt_{max(point)}$ is possible but to produce an experimental record of the pressure history within the entire lung (needed to calculate P_{max} and dP/dt_{max}) is impractical.

Two tests together allow each criterion to be critically assessed to determine whether it is likely to be a reliable indicator of the expected injury level:-

- Test 1. Do the criteria correctly indicate the effect of changing the four impact parameters? For example, increasing impactor mass (with other factors constant) should increase the indicated level of injury. If it does not, then the criterion must be considered suspect.

- Test 2. Do the criteria correctly reflect the factors which will actually give rise to contusion? That is, do the criteria actually give an indication of the overall levels of dP/dt achieved throughout the lung?

Injury indices based on Criteria 1-10 have been calculated for each impact case. This enables the way in which expected level of injury varies with each of the four parameters given in Section 2.3 to be determined.

4. RESULTS

4.1 Test 1 - Ability to Follow Expected Trends

Figures 3-9 show the way in which Injury Indices based on Criteria 1-10 vary with thorax size, impactor mass, impact velocity and lung density. It should be noted that the graphs are not plotted from zero on the horizontal axis and that the values shown for "Injury" are normalised to allow comparison between cases. Therefore, the curves do not show absolute injury levels for particular cases but rather show relative degree of injury.

It can be seen that in most cases the criteria do show the trends which would be expected although there are exceptions.

- Injury would be expected to decrease as thorax "size" increased. However, this trend would not be predicted if $A_{max(ext)}$ were used as the injury index (Figure 3). This casts doubt on the suitability of maximum chest wall outer surface acceleration as an injury index. $VC_{max(ext)}$ is better but is still unable to take this effect fully into account. The other criteria, however, do show the expected behaviour.

- As impactor mass increases so all injury criteria would predict worse injuries (as expected) except $A_{max(ext)}$ which predicts exactly the opposite. This result sheds further doubt on the validity of maximum chest wall outer surface acceleration as an injury predictor.

- All ten criteria predict worse injury as impactor velocity is increased. This result is certainly a real effect.

- Criteria 1-5 do not predict any change in injury level as lung density varies. Criteria 6-10 predict increasing injury as lung density rises. Changing lung density almost certainly does have an effect on injury level although of course for any given type of thorax (eg. all humans) lung density might reasonably be expected to remain fairly constant between examples. Thus, this result is felt to be rather less important than the previous three.

From this exercise $A_{max(ext)}$ has been shown to be extremely unreliable as an indicator of injury level. The remaining criteria give much better results although it is clear from the figures that some yield rather smoother relationships than others.

4.2 Test 2 - Comparison with $dP/dt_{max(mean)}$

As discussed in Section 3.3, $dP/dt_{max(mean)}$ is considered to be a good indicator of injury level as it takes account of the value of dP/dt across the whole lung section. However, this injury index is not particularly simple to determine from the modelling and would be virtually impossible to determine from experiment. Although the other indices do not directly take both of these factors into account, some of them may give similar predictions of injury level. To test this hypothesis, Figures 10-18 show injury indices based on Criteria 1-9 plotted against that predicted by $dP/dt_{max(mean)}$. It should be noted that the cases which considered different lung densities are not plotted on these figures.

A "perfect" result would give a smooth relationship between the values predicted by the two criteria but in fact it can be seen that very different results are obtained for different cases. A number of results are particularly significant:-

- $VC_{max(int)}$ gives good agreement with $dP/dt_{max(mean)}$ (Figure 10) but if instead the external motion is used to calculate VC (Figure 11) then less reliable results are obtained. In fact, the points which lie off the main curve are those which result from changing the thorax size and $VC_{max(ext)}$ is unable to take this fully into account (see Section 4.1). Again this is because it is the internal rather than external motion which is actually applied to the lung and which therefore dictates the pressures generated in the parenchyma.

- $V_{max(int)}$ (Figure 12) also gives very good results. The relationship is not linear but this would not be expected as previous work has shown that the pressures generated in the lungs increase more and more rapidly as velocity rises.

- $A_{max(int)}$ (Figure 13) is quite a good indicator of injury but $A_{max(ext)}$ (Figure 14) is very poor indeed. It is not surprising that $A_{max(int)}$ gives good results. Pressure generated in the lung is known to be a function of velocity of deformation. Therefore rate of change of pressure, which is the factor which causes contusion, would be expected to be a function of rate of change of velocity. Nor is it particularly surprising that external acceleration gives poor results as it is not the external motion which actually deforms the lung.

- Criteria 6-9, using output from the DYNA2D models (Figures 15-18) show good agreement with $dP/dt_{max(mean)}$. This result suggests that the pressure conditions which are produced in the lung follow similar patterns for all cases, with broadly similar temporal and spatial distributions. This is because the lung is a similar shape in each case and the deformation applied to the lung is of a similar form, varying only in amplitude and duration. Thus, the most damaging conditions would always be expected to occur at the same site in the lung for any given type of impact. However, the indices calculated using these criteria for one type of impact cannot then be directly compared with indices from a different type of impact. Instead, it would be necessary to analyse further finite element models to determine the nature of the overall pressure distribution for the new case.

4.3 Implications of Test Results

The results described above have important implications.

- For any given type of impact it is sufficient to measure or otherwise determine the pressure conditions (Pressure or dP/dt) at just one point in the lung and then use this as a relative injury index. However, the result cannot then be compared with indices from a different type of impact without analysing further finite element models.

- The most accurate contusion injury criteria will take into account the maximum rate of change of pressure across the whole lung. However injury indices based on such criteria are not particularly easy to determine from modelling and would be virtually impossible to determine experimentally.

- For a given type of impact, $V_{max(int)}$ has been shown to give a very good indication of the expected level of injury although the relationship is not linear.

- It has been shown that maximum acceleration based on external motion (eg. the chest wall outer surface) is not a reliable indicator of the expected level of injury for this type of non-penetrating impact. However, if internal acceleration is used then much better results are obtained.

- Viano's Viscous Criterion is widely used as an indicator of the likely severity of injury and has been shown to agree well with experimental results (Reference 3). The work described above now shows **why** this is so. Although VC (ie. displacement x velocity) is not of itself the injury producing condition, it has been shown that it is a good indication of the levels of dP/dt which are generated in the lung and is therefore a good indicator of the likelihood of capillary bursting and hence of contusion injury. However, VC based on external motion does not fully take account of changes in thorax size and so comparison between different types or sizes of thorax must be carried out with care.

6. CONCLUSIONS

Table 1 summarises the relative merits of the injury criteria which have been assessed. It can be seen that, in general, the most reliable injury indices are also the most difficult to determine from experiment. Conversely, those indices which are easily determined are often very poor indicators of the extent of injury. This is somewhat less than helpful!

Criterion	Ease of Determination		Reliability
	Experiment	Modelling	
1. $VC_{max(int)}$	Moderate	Very good	Good
2. $VC_{max(ext)}$	Fair	Very good	Poor
3. $V_{max(int)}$	Moderate	Very good	Good
4. $A_{max(int)}$	Moderate	Very good	Good
5. $A_{max(ext)}$	Fair	Very good	Very poor
6. P_{max}	Very difficult	Moderate	Good
7. dP/dt_{max}	Very difficult	Moderate	Good
8. $P_{max(point)}$	Difficult	Good	Good
9. $dP/dt_{max(point)}$	Difficult	Good	Good
10. $dP/dt_{max(mean)}$	Very difficult	Moderate	Very Good

Table 1: Comparison of Lung Contusion Injury Criteria

Acceleration of the outside of the chest wall has been shown to be a very poor indicator of the conditions which actually cause the injury.

VC_{max} based on external motion is the most readily determined index which seems to have any merit at all although even this index is not particularly reliable as it is does not fully take into account the effect of changes in thorax size.

If chest wall internal motion can be determined then maximum velocity, acceleration or VC based on this motion would be expected to give good results.

The best results of all can be expected from criteria which actually take into account the distributions of pressure and dP/dt throughout the whole lung but determination of corresponding injury indices from experiment is generally impractical. Of course this highlights the enormous advantage of mathematical modelling which can determine values for the injury indices without undue difficulty!

7. FUTURE DEVELOPMENTS

Two further developments of the method described in this paper would provide additional insight into the problem. Alternative impact cases could be analysed to determine whether the criteria can be used to "read across" from one impact case to another (it is likely that many of them cannot). In addition, more detailed comparison between the results of modelling and experimental findings is already being undertaken. This will allow other injury criteria to be derived (for example the proportion of the lung in which dP/dt exceeds a given threshold value) which may reflect the mechanisms which actually cause contusion more closely and which may give even better correlation with observed behaviour.

8. ACKNOWLEDGEMENTS

This work has been carried out with the support of the Procurement Executive, Ministry of Defence. Special thanks are due to Dr G.J. Cooper of the Chemical Defence Establishment, Porton Down, for his specialist advice and assistance during the study.

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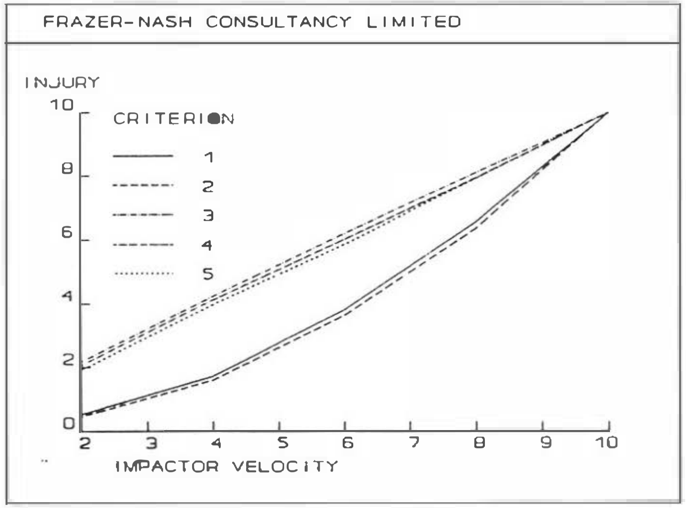

Figure 7: Effect of Impactor Velocity (a)

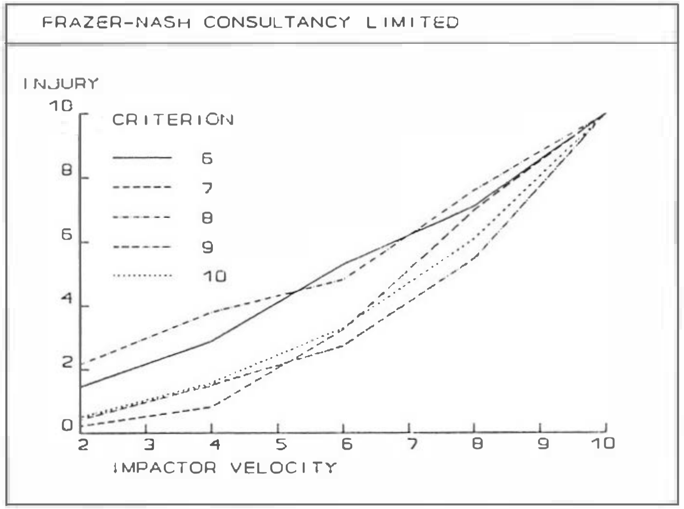

Figure 8: Effect of Impactor Velocity (b)

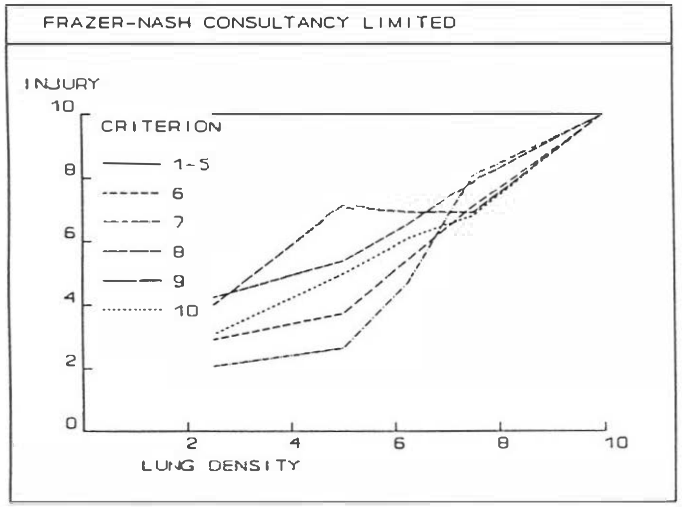

Figure 9: Effect of Lung Density

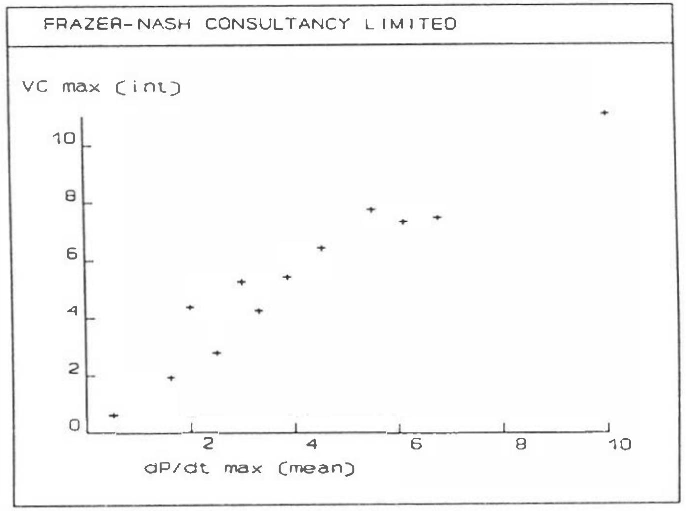

Figure 10: $VC_{max(int)}$ vs $dP/dt_{max(mean)}$

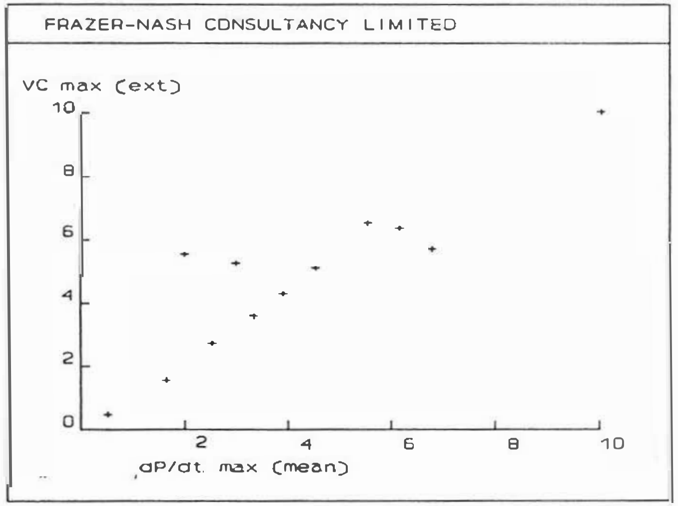

Figure 11: $VC_{max(ext)}$ vs $dP/dt_{max(mean)}$

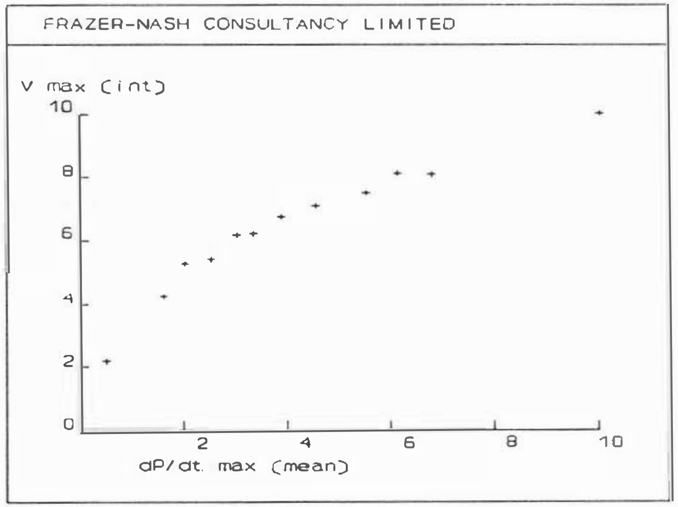

Figure 12: $V_{max(int)}$ vs $dP/dt_{max(mean)}$

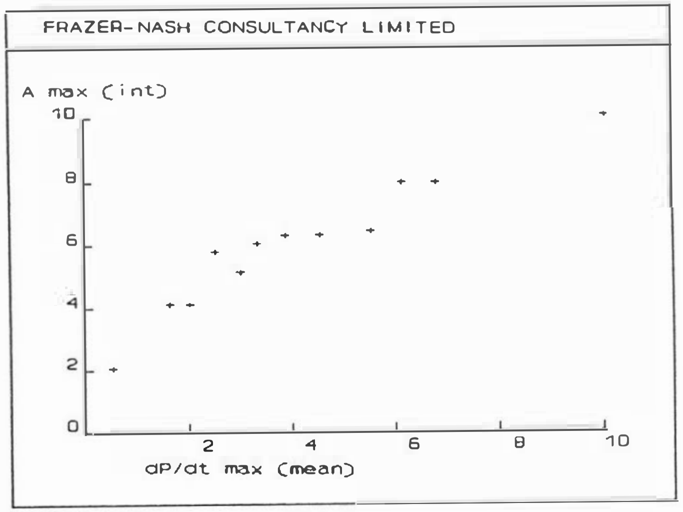

Figure 13: $A_{max(int)}$ vs $dP/dt_{max(mean)}$

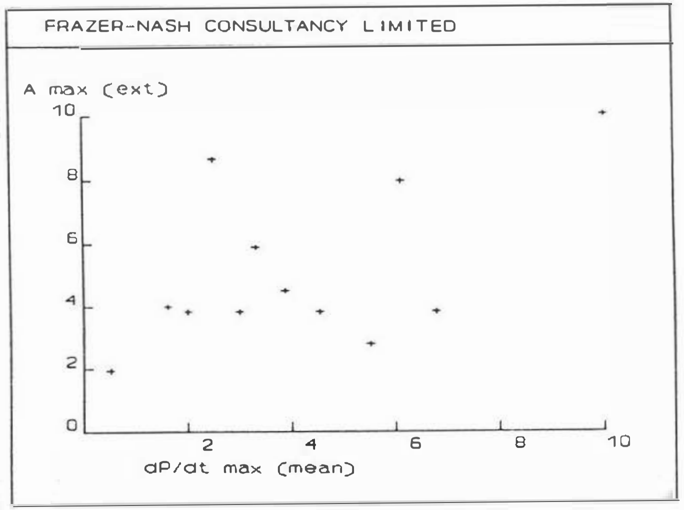

Figure 14: $A_{max(ext)}$ vs $dP/dt_{max(mean)}$

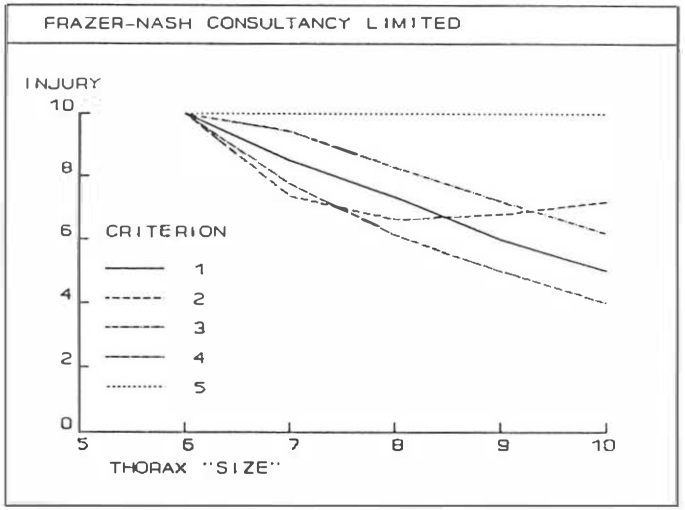

Figure 3: Effect of Thorax Size (a)

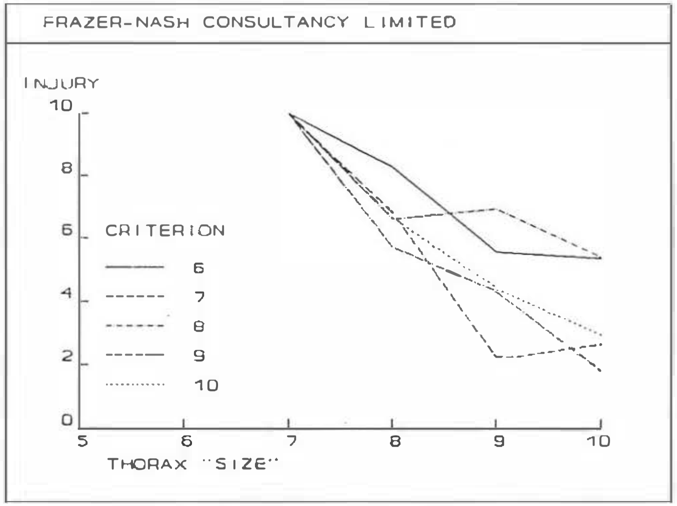

Figure 4: Effect of Thorax Size (b)

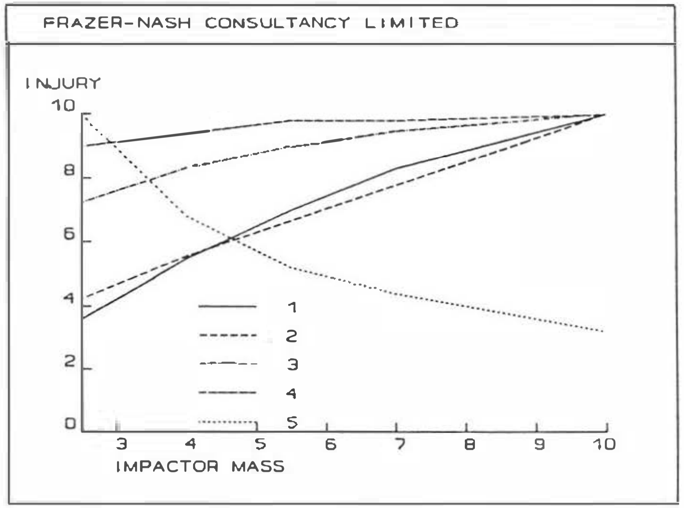

Figure 5: Effect of Impactor Mass (a)

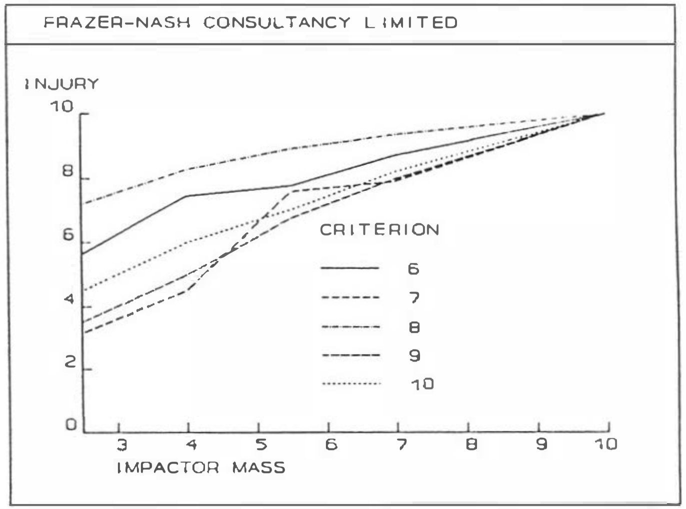

Figure 6: Effect of Impactor Mass (b)

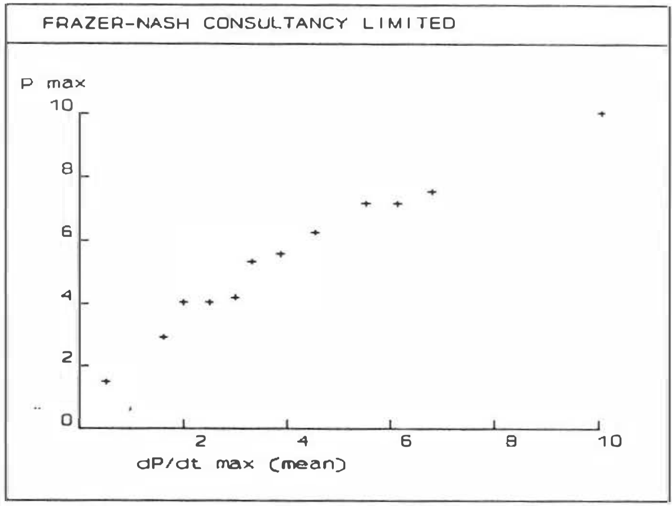

Figure 15: P_{max} vs $dP/dt_{max(mean)}$

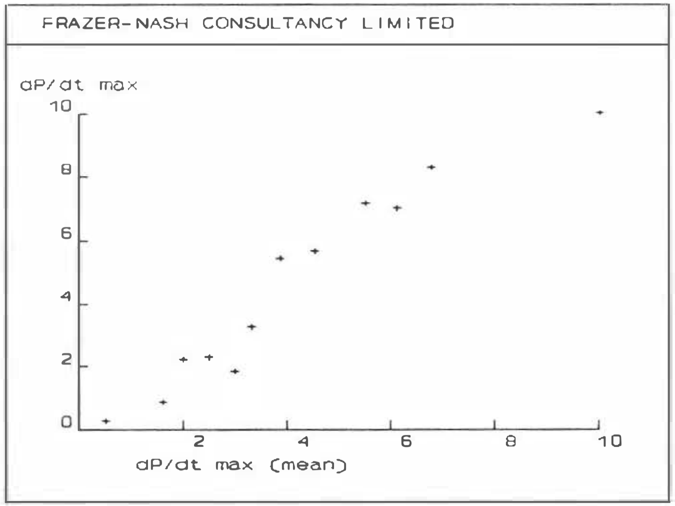

Figure 16: dP/dt_{max} vs $dP/dt_{max(mean)}$

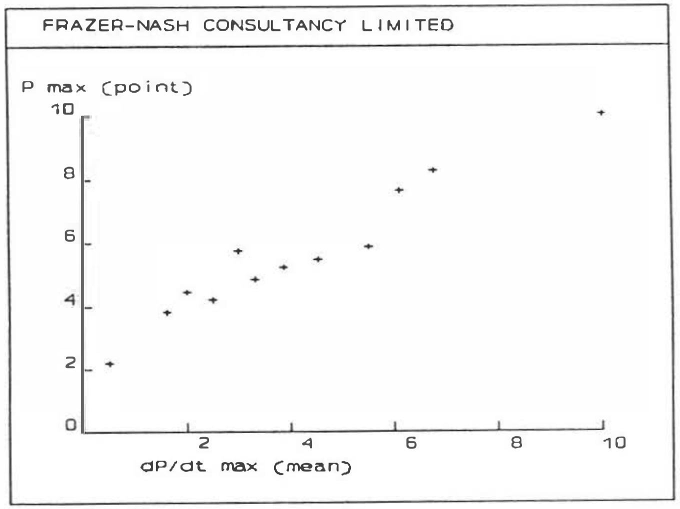

Figure 17: $P_{max(point)}$ vs $dP/dt_{max(mean)}$

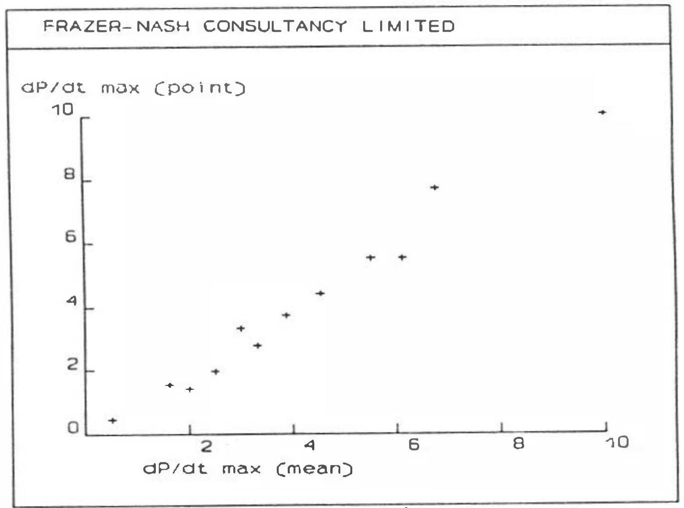

Figure 18: $dP/dt_{max(point)}$ vs $dP/dt_{max(mean)}$