THE APPLICATION OF THE NEW MEAN STRAIN CRITERION (NMSC)

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ABSTRACT

The Mean Strain Criterion (MSC) is now over ten years old. This head injury criterion was formulated on many head impacts to subhuman primates and then extrapolated to humans by dimensional analysis. Also, the connection between force-time input for the primates and acceleration-time input for dummies was made without justification. Add to this a recent interest in having a head injury criterion which predicts AIS numbers 0 through 6 and it becomes of interest to rework the MSC into a new criterion.

This study, based on the MSC concept, inputs the head impact force from cadaver head impacts into the MSC mechanical impedance two-mass head models to generate a new criterion, "The New Mean Strain Criterion" (NMSC). This was done by remodeling the old MSC head impedance model for four directions.

The model system equations were then solved to obtain the model input force and the model output deflection. The deflection was then used to obtain the human equivalent strain and strain rate, and thus, the potential for injury.

The results show that given a force-time trace for humans or an acceleration-time trace for dummies, the NMSC is useful in predicting the potential for injury during a translational head impact.

INTRODUCTION

Research to establish a head injury criterion has been going on for more than twenty years. As a consequence of this research, a number of criterion have been proposed, The Vienna Institute Index (JII) [1], the Effective Displacement Index [2] (EDI), the Revised Brain Model (RBM) [3], the Gadd Severity Index (GSI) [4], and the Head Injury Criterion (HIC) [5,6], all of which are derived from the Wayne State Tolerance Curve (WSTC) [7,8]. In addition to these criteria, two more have been proposed which were not derived from the WSTC. These two are the
JARI Human Head Impact Tolerance Curve (JHTC) [9] and the Mean Strain Criterion (MSC) [10,11]. One of these two, the Mean Strain Criterion (MSC) is the only one based on an experimentally determined head model and validated on living subhuman primates and cadavers over the full AIS scale of 0 to 6.

The MSC model was first published by Stalnaker et al. in 1970 [10]. The MSC criterion was then published by Stalnaker et al., in 1971 [11]. These two papers describe in detail the experiments using subhuman primates which led to the establishment of the MSC. Dimensional analysis techniques were used to extrapolate the MSC to humans.

In spite of direct competition from the then newly formed Head Injury Criterion (HIC), the MSC began to be used among researchers and safety-design engineers. However, because the MSC was developed using separate head models, i.e., lateral and frontal, and was based on limited cadaver information, the MSC soon gave way to the HIC in confusion and misunderstanding.

In the last few years, increased interest in the cost effectiveness of automotive interior design changes has renewed interest in the MSC, mainly because the MSC is a continuous criterion with respect to head injury.

The confusion and misunderstanding of the MSC can be solved by up-dating the criterion into four directional models (Anterior-Posterior (A-P), Posterior-Anterior (P-A), Superior-Inferior (S-I), and Left-Right (L-R)), redefining the model inputs and outputs, and updating the injury criterion with additional primate and cadaver data obtained in the last fifteen years.

The New Mean Strain Criterion (NMSC) is demonstrated by using nine tests to predict head injury. The results of this study show that the NMSC can be used inexpensively and uniquely to evaluate head injury.*

**METHOD**

The old MSC criterion is based on a series of mechanical impedance experiments which allowed the conceptual characterization of the head with two masses coupled by a spring and dashpot (Figure 1). The parameter D (cranium distance) reported in the original work was based on the single cadaver used in the dimensional analysis [12].

For head impacts of a known force the resulting injuries could be grouped by comparing the mean strain, as predicted by the model, with injury levels. Mean strain is defined as the

*The complete justification of the material presented here is in preparation for publication in the near future.
displacement of one mass of the model relative to the other mass, divided by the distance across the cranium. By assuming that the brain is equally vulnerable to strain in all directions, the relationship between the strain value and the injury in any direction was plotted (Figure 2).

![Diagram](attachment:image.png)

<table>
<thead>
<tr>
<th>$M_1$ (kg)</th>
<th>$M_2$ (kg)</th>
<th>$C$ (N·sec/m)</th>
<th>$K$ (N/m)</th>
<th>$D$ (m)</th>
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</thead>
<tbody>
<tr>
<td>0.1814</td>
<td>4.0823</td>
<td>420.30</td>
<td>455300</td>
<td>0.146</td>
</tr>
</tbody>
</table>

Fig. 1. Old MSC Model and Parameters.

Fig. 2. Old MSC Injury Equivalent.

In up-dating the old MSC criterion, there were four steps to be taken. First, the mechanical impedance model had to be reevaluated. Second, the dynamic equation of the newly formed impedance models had to be written. Third, new injury levels had to be determined, based on new and old injury data. Last, it was necessary to determine how to use the new criterion.

NEW MECHANICAL IMPEDANCE MODELS--The original primate mechanical impedance studies had mechanical impedance curves in four directions, (A-P, P-A, L-R, and S-I), but the human impedance curves were only for the A-P and L-R directions. Since that earlier work, the mechanical impedance response for humans in the P-A and S-I has been measured. The original human mechanical impedances and subsequent model responses are shown in Figures 3 and 4.

As can be seen from Figures 3 and 4, the impedance model does not fit the data at the antiresonant. Also, because the human impedance data was taken for individuals with different head masses and head material properties, the models for each direction have to be standardized to a single head with compatible head material properties.
The impedance models were modified by incorporating a damping element in series with the spring in the old MSC model so that good agreement between model and data was achieved. The head mass for the human impedance data was normalized to the human head data used to define the Hybrid III Head [13].

The new models were then fit to the impedance data by varying the model parameters. Once the model parameters were determined for each head direction, the head total mass was fixed to 4.5359 Kg and the spring and two damper values were examined. The parameters that appeared to be constant were averaged and the others were looked at to see if they were consistent with the reality of the loading. The new mechanical impedance model is given in Figure 5. The NMSC Impedance Models with the model parameters are given in Figures 6 through 9.

NEW MODEL IMPACT EQUATIONS--The old MSC model was a one-dimensional, two degree-of-freedom model which was reduced to a one degree-of-freedom model by setting \( F(t) \) equal to \( M_1 \) times a measured acceleration \( a(t) \). This model was good only for the cases where acceleration was known at the point of impact.

The NMSC model is a one-dimensional, three degree-of-freedom model with a force \( F(t) \) input to mass \( M_1 \) of the model (Figure 10). Therefore, given a rigid head impact as a function of time and the impedance model parameters, the system equations can be solved for \( X_1, X_2, X_3, \dot{X}_1, \dot{X}_2, \dot{X}_3 \). These variables and combinations of variables can be correlated to injuries from impacts.
Fig. 5. -- New MSC Head Model

Fig. 6. Cadaver Mechanical Impedance Model and New MSC Model Responses in A-P Direction

Fig. 7. Cadaver Mechanical Impedance Model and New MSC Model Responses in P-A Direction

Fig. 8. Cadaver Mechanical Impedance Model and New MSC Model Responses in L-R Direction

Fig. 9. Cadaver Mechanical Impedance Model and New MSC Model Responses in S-I Direction
NEW INJURY LEVELS--In developing the old MSC the head acceleration was determined by film analysis and Newton's Second Law using total head mass and the measured force. The two accelerations were compared and an average was used as input to the old MSC model. The relative displacement between the two model masses was normalized by an average head length for that species in the direction of impact. The maximum "strain" was then correlated with the Estimated Severity of Injury (ESI) and a relationship determined for that species between "strain" and injury. This procedure was repeated for five species of primates. These results and dimensional analysis were used to extrapolate the injury strain levels to humans. From the primate studies the same strain number was found for a given injury level independent of the direction of impact. So, for humans it was assumed that equal strains in any direction would give equal injury. Once this was known, the head impedance model in any direction could be determined.

All of the above work was for lateral head impacts. The impedance model for human frontal (A-P) response was then determined, and using the assumed constant MSC strain number, injury in frontal impacts could be assessed.

Over the last 15 years, many primate head impacts have been conducted, many with 6 or 9 accelerometers on the head [14,15], also a large number of cadaver head impacts have been conducted, with similar accelerometer configurations [16,17,18,19,20]. These head impacts were in all four directions. A-P, P-A, L-R, and S-I, and most had force, head acceleration, and injury (AIS). With this very large data set the NMSC head models (both primate and cadaver and in any of the four above mentioned directions) could be exercised and the model output correlated to AIS.

This was accomplished by noting that AIS rankings for rigid head impacts correlated highly with strain (e) and strain rate.

Fig. 10. NMSC Head Injury Model and Governing Equations.

\[ F = M_1 \ddot{x}_1 + K(x_1 - x_3) + C_2(\dot{x}_1 - \dot{x}_2) \]  

\[ M_2 \ddot{x}_2 = C_1(\dot{x}_3 - \dot{x}_2) + C_2(\dot{x}_1 - \dot{x}_2) \]  

\[ K(x_1 - x_3) = C_1(\dot{x}_3 - \dot{x}_2) \]
(\dot{\epsilon}). Because of this, head injury was felt to be a function of both \epsilon and \dot{\epsilon}. Each cadaver rigid head impact was plotted, \dot{\epsilon} as a function of \epsilon, and marked by its AIS number.

The relationship between \epsilon and \dot{\epsilon} was then established for each AIS injury level, and then for each of the four impact directions A-P, P-A, L-R, and S-I, symmetry was noted between A-P, P-A, and L-R, R-L. The injury functions for the four directions are given in Table 1.

<table>
<thead>
<tr>
<th>Impact Directions</th>
<th>Threshold of Strain Rate</th>
<th>Injury Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>0.705</td>
<td>\text{AIS} = 3.8698 \ln (920 \epsilon + \dot{\epsilon}) - 8.9355</td>
</tr>
<tr>
<td>PA</td>
<td>0.705</td>
<td>(Same as above)</td>
</tr>
<tr>
<td>LR</td>
<td>2.580</td>
<td>\text{AIS} = 7.0231 \ln (920 \epsilon + \dot{\epsilon}) - 24.3850</td>
</tr>
<tr>
<td>SI</td>
<td>0.400</td>
<td>\text{AIS} = 6.8463 \ln (920 \epsilon + \dot{\epsilon}) - 24.0795</td>
</tr>
</tbody>
</table>

A threshold strain rate level (\dot{\epsilon}_T) was set for each impact direction. These levels were based on the evaluation of cadaver padded head impacts using the given AIS value and the threshold strain rate. It was necessary to establish this lower strain rate level because the NMSC head models could not be modeled for pulse durations above 200 msec. The \dot{\epsilon}_T for which the NMSC head models can be used are given in Table 1. These minimum values of strain rate are so low that any injury potential due to strain rate below these threshold values are believed to have no injury capability.

APPLICATION OF THE NEW MSC — The NMSC is applied by taking the three center of gravity (C.G.) translational accelerations as functions of time and inputting these accelerations into the appropriate models as the acceleration of mass 2 (M_2). By solving the system equations (Fig. 10), force F(t) at mass 1 (M_1) as well as the model strain, and strain rate in each direction are obtained. All values of strain rates less than \dot{\epsilon}_T are set to zero until the strain rate exceeds \dot{\epsilon}_T. At that time strain and strain rate are recorded until strain rate falls below \dot{\epsilon}_T again. The strain is held at that value until once again strain rate exceeds \dot{\epsilon}_T. At that time, strain begins to accumulate with higher strain rate, and so on.
Once strain and strain rate are obtained for a given direction, the AIS number for that direction is calculated by applying strain and strain rate in the appropriate equation shown in Table 1. The injury lever is a function of time as is strain and strain rate. By picking the maximum AIS number the injury potential in the given direction is obtained. Also, the component force for that direction can be solved for by using the equations shown in Figure 10. Now repeat this procedure for the other two directions. Once this is done, the AIS numbers and the component forces in each of the three principle directions are known. So, with three AIS numbers and the resultant impact force, the NMSC for a given test is known. The flow chart of the NMSC is shown in Figure 11.

Fig. 11. The NMSC Head Injury Criterion Flow-Chart.

The following rule should be followed when using the NMSC:

1. For A-P direction impacts, use A-P model.
2. For P-A direction impacts, use P-A model.
3. For L-R or R-L direction impacts, use L-R model.
4. For S-I or I-S direction impacts, use S-I model.

Since the relationship between cadaver and dummy is not yet fully established, and because the negative strain rate may be the cause of contreco up injuries in cadavers the absolute value of both strain and strain rate are used for dummy applications.

RESULTS AND DISCUSSION

Six Part 572 dummy head impacts (21), (22), and (23), two cadaver belted tests (24), and one volunteer test (25) are used to demonstrate the uses of the NMSC head injury criterion.

The results of the examples used to demonstrate the use of the NMSC are given in this section. The examples chosen for this demonstration cover a wide range of possible uses of the NMSC.
It should be noted that the resulting AIS numbers only indicate the injuries due to contusion type brain injuries (not contrecoup). That is, the test condition may cause rotational type injuries or skull fracture which are not reflected in the AIS numbers obtained from the NMSC. The force output of the NMSC model can be used to give an indication of potential skull fracture. Also, this study assumes that the accelerations recorded in the dummy are the same as would be seen in a cadaver under the same loading conditions.

The NMSC model input C.G. accelerations for each example are given in Figures 12 through 37. The NMSC model resultant impact force for each example is given in Figures 38 through 43. A summary of the tabular results are shown in Table 2.

The first example is a standard calibration test for a Part 572 head dropped from 0.33 meters. The results show an NMSC AIS injury number of 2.81 for the A-P direction. The other two directions have zero injury AIS readings. The HIC for this test was calculated to be 1,033. A peak force on the forehead of 10,681 newtons was predicted by the NMSC model. This force value would indicate a probability of skull fracture.

The second example is the same as the last but dropped from only 0.19 meters. The predicted AIS injury number was found to be 0.49 for the A-P direction and a HIC was calculated to be 358. The peak force was found to be only 6,761 newtons and was believed not to cause skull fracture.

The next example involves a 48 km/hr HYGE sled test with an unrestrained Part 572 in the driver's seat into the windshield. The buck used in this test was of a 1979 Mercury Zephyr. The results of the NMSC are AIS numbers of 1.24 for the A-P direction, 2.89 for the S-I direction, and zero for the L-R direction. The HIC calculation for this test was 817. The resultant head impact force as predicted by the NMSC model was 29,735 newtons. This would represent a very high probability of skull fracture.

The next example was a repeat of the previous example. The results of this test give AIS numbers predicted by the NMSC of 3.18 A-P, 1.70 L-R, and 0.33 for the S-I direction. The HIC was calculated for this test was 2,097. The predicted force for this test was 18,262 newtons. This also would indicate a very high probability of skull fracture.

A rigid pole impact at 45° into the driver's side of a VW Rabbit was used for the next example. A SID Dummy was used in this test. The dummy's head went out the side window and impacted the pole. The result of this test was an AIS number of 1.67 in the A-P direction. The AIS in the other directions were zero. The HIC was found to be 977. The resultant force was found to be 9077 newtons. This force value would indicate a high probability of skull fracture.
The last example of a dummy test is a Romeo-Kojyo Airbag Sled Test. A Part 572 Dummy was used. In this test, the NMSC predicted AIS injury numbers were all zero. The HIC was calculated to be 502. The peak force on the head in this test was only 2491 newtons. This force was very low.

The next two examples were 51.2 km/hr 3-point belted cadaver sled tests on the standard GM Rigid Seat. The cadavers were fully instrumented so the three head C.G. accelerations were known. The results of these two tests for predicted AIS numbers are all zero. The HIC was 659 in the first test and 353 in the second test.

The final example was for the most severe NBDL volunteer test. The sled velocity was 4.78 km/hr and a peak acceleration of 15 G's. The HIC was 90, and the NMSC indicated all AIS numbers of zero.

The NMSC, as used now, gives three AIS values, AISx, AISy, and AISz. These three AIS values combined will give a more serious injury than just the highest AIS alone. In Table 3, a list of all combinations of three AIS values and the probability of death is given. This is based on the AIS-80 definitions of, 1-minor, 2-moderate, 3-serious, 4-severe, and 5-critical, and was determined from the National Accident Sampling System (NASS) involving some 35,000 injuries persons with three AIS injuries.

Take the head drop test at 0.33 meters drop height as an example. A head impact evaluation yields AISx = 2.81, AISy = 0, and AISz = 0, then the 3-AIS ranking code in Table 3 will yield about 1.8% probability of death. In this study, all of the examples were evaluated in this way. The summary of all AIS numbers and probability of death for the examples is listed in Table 2.

The combination of three AIS numbers to predict a probability of death is a suggested way to deal with the combining of AIS injury numbers. Other methods may be acceptable.

Finally, a sine wave force with a peak value of 6,000 newtons is input to each direction to compare the sensitivity to injury for the four impact directions. The results give AIS numbers of 1.47 A-P, 1.14 P-A, 3.41 L-R, and a zero for the S-I direction. This shows that, for the same level of impact force, the L-R direction may be more vulnerable than the A-P, P-A, and S-I directions. The results, however, may vary with the shape of input functions.
TABLE 2
Summary of Dummy Tests

<table>
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<tr>
<th>Description</th>
<th>Test Number</th>
<th>HIC</th>
<th>Direction</th>
<th>AIS</th>
<th>Probability of Death (%)</th>
<th>References</th>
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<tr>
<td>Standard Part 572</td>
<td>57COH001</td>
<td>1033</td>
<td>A·P</td>
<td>L-R</td>
<td>2.81</td>
<td>(21)</td>
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<td>Head Drop 0.33 m</td>
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<td></td>
<td>L-R</td>
<td>0</td>
<td>1.8%</td>
<td></td>
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<tr>
<td>Standard Part 572</td>
<td>57COH004</td>
<td>358</td>
<td>A·P</td>
<td>L-R</td>
<td>0.49</td>
<td>(21)</td>
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<td>Head Drop 0.19 m</td>
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<td></td>
<td>L-R</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Sled (Zephyr) Unrestrained</td>
<td>572IDDU34</td>
<td>817</td>
<td>A·P</td>
<td>L-R</td>
<td>3.18</td>
<td>(21)</td>
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<td>Driver Windshield Impact 48 Km/hr</td>
<td></td>
<td></td>
<td>L-R</td>
<td>0.33</td>
<td>2%</td>
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<td>Sled (Zephyr) Unrestrained</td>
<td>572IDDU15</td>
<td>2097</td>
<td>A·P</td>
<td>L-R</td>
<td>1.70</td>
<td>(21)</td>
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<td>Driver Windshield Impact 48 Km/hr</td>
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<td></td>
<td>L-R</td>
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<td>VW Rabbit Into Fixed Pole (45°)</td>
<td>840629</td>
<td>977</td>
<td>A·P</td>
<td>L-R</td>
<td>1.67</td>
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<td>Driver Romeo-Kojyo</td>
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<td>0</td>
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<td>Airbag Sled Test</td>
<td>0583222</td>
<td>502</td>
<td>A·P</td>
<td>L-R</td>
<td>0</td>
<td>(23)</td>
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<td>Cadaver Belted Test</td>
<td>768001</td>
<td>659</td>
<td>A·P</td>
<td>L-R</td>
<td>0</td>
<td>(24)</td>
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<tr>
<td>Standard GM Bench Seat</td>
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<td></td>
<td>L-R</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Cadaver Belted Test</td>
<td>768006</td>
<td>353</td>
<td>A·P</td>
<td>L-R</td>
<td>0</td>
<td>(24)</td>
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<td>Standard GM Bench Seat</td>
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<td>L-R</td>
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<td>NBDL Volunteer Test</td>
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<td>90</td>
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<tr>
<td>S·I</td>
<td></td>
<td></td>
<td>L-R</td>
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*AIIS and Probability of Death*, in preparation for publication.

TABLE 3
Ranking of 3-AIS Codes

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<th></th>
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<tr>
<td>1</td>
<td>100</td>
<td>0.00</td>
<td>15</td>
<td>322</td>
<td>0.04</td>
<td>29</td>
<td>433</td>
<td>0.27</td>
<td>43</td>
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<td>2</td>
<td>110</td>
<td>0.00</td>
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<td>442</td>
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<td>210</td>
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Fig. 12. Standard Part 572 Drop Test (X-Direction).

Fig. 13. Standard Part 572 Drop Test (Y-Direction).

Fig. 14. Standard Part 572 Drop Test (Z-Direction).

Fig. 15. Standard Part 572 Drop Test (X-Direction).

Fig. 16. Standard Part 572 Drop Test (Y-Direction).

Fig. 17. Standard Part 572 Drop Test (Z-Direction).
Fig. 18. Sled (Zephyr) Unrestrained Driver-Windshield (X-Direction).

Fig. 19. Sled (Zephyr) Unrestrained Driver-Windshield (Y-Direction).

Fig. 20. Sled (Zephyr) Unrestrained Driver-Windshield (Z-Direction).

Fig. 21. Sled (Zephyr) Unrestrained Driver-Windshield (X-Direction).

Fig. 22. Sled (Zephyr) Unrestrained Driver-Windshield (Y-Direction).

Fig. 23. Sled (Zephyr) Unrestrained Driver-Windshield (Z-Direction).
Fig. 30. Cadaver Belted Test on Standard GM Bench Seat (X-Direction).

Fig. 31. Cadaver Belted Test on Standard GM Bench Seat (Y-Direction).

Fig. 32. Cadaver Belted Test on Standard GM Bench Seat (Z-Direction).

Fig. 33. Cadaver Belted Test on Standard GM Bench Seat (X-Direction).

Fig. 34. Cadaver Belted Test on Standard GM Bench Seat (Y-Direction).

Fig. 35. Cadaver Belted Test on Standard GM Bench Seat (Z-Direction).
Fig. 3.6. Naval Biodynamics Laboratory Volunteer Test (X-Direction).

Fig. 3.7. Naval Biodynamics Laboratory Volunteer Test (Z-Direction).

Fig. 3.8. Standard Part 572 Drop Test (Resultant Force).

Fig. 3.9. Standard Part 572 Drop Test (Resultant Force).

Fig. 3.10. Sled (Zephyr) Unrestrained Driver-Windshield (Resultant Force).

Fig. 3.11. Sled (Zephyr) Unrestrained Driver-Windshield (Resultant Force).
CONCLUSIONS

1. The NMSC has been fully defined for contusion type head injuries in cadavers for pulse durations of less than 200 msec.

2. The NMSC head models are capable of predicting impact force to the head of cadavers.

3. Dummy heads must be designed to human-like impact response data before the forces and AIS number predicted by the NMSC are fully comparable.

4. The NMSC allows the user to better understand the make-up of direct head impacts by giving the contribution of contusion type injury and skull fracture to the overall head injury.

5. The NMSC reflects directional impact sensitivity to the head of cadavers.

6. The NMSC indicates that for a given head impact in each of the four model directions, the order of severity from most severe to least severe is L-R, A-P, P-A, and S-I.

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