INTRODUCTION

Automobile collisions may result in soft-tissue injuries to the cervical spine leading to chronic symptoms. In order to predict these injuries, a validated cervical spine injury criterion is needed. The Neck Injury Criterion (NIC) is based on the hypothesis that sudden changes in spinal fluid pressure may cause neural injuries, and was formulated using a rear impact porcine model (Bostrom et al., 1996). The Intervertebral Neck Injury Criterion (IV-NIC) is based on the hypothesis that intervertebral motion beyond the physiological limit may injure cervical soft tissues (Panjabi et al., 1999). The goals of this study were to use a biofidelic whole human cervical spine model with muscle force replication in frontal impact simulations to determine the IV-NIC injury threshold at each intervertebral level, and to compare IV-NIC with NIC.

METHODS

The IV-NIC was defined as the dynamic intervertebral rotation during simulated frontal impact, $\theta_{\text{dynamic}, i}(t)$, divided by the corresponding physiological range of motion (ROM) limit, $\theta_{\text{physiological}, i}$, where $i$ is the intervertebral level. Thus,

$$ IV - NIC_i(t) = \frac{\theta_{\text{dynamic}, i}(t)}{\theta_{\text{physiological}, i}}, $$

(1)

where $t$ represents time.

The NIC is given by the following equation:

$$ NIC(t) = 0.2 \cdot a_{rel}(t) + v_{rel}^2(t), $$

(2)

where $a_{rel}(t)$ and $v_{rel}(t)$ are the relative horizontal acceleration and velocity, respectively, between the head center of mass and T1 vertebra.

Six intact human osteoligamentous cervical spine specimens (occiput to T1) were prepared with vertebral motion tracking flags. The flags, each with two white, spherical, radio-opaque markers, were attached to each vertebra. Sagittal flexibility testing up to 1.5 Nm was performed to determine the intervertebral flexibility parameters of neutral zone (NZ) and ROM of the intact specimens and following each frontal impact. The whole cervical spine with muscle force replication and surrogate head were used to simulate frontal impacts at 4, 6, 8, and 10 g horizontal accelerations of the T1 vertebra using a bench-top sled (Panjabi et al., 1998). A high-speed camera recorded the spinal motions at 500 frames/sec. Accelerometers were mounted to the sled and head center of mass to determine the T1 and head horizontal accelerations, respectively. The IV-NIC and NIC were computed as functions of time using equations (1) and (2), respectively.

The soft tissue injury was defined as a statistically significant increase ($p<0.05$) in NZ or ROM, due to frontal impact simulation above the corresponding baseline...
values. The soft tissue injury threshold was the lowest T1 horizontal peak acceleration that caused the soft tissue injury. The IV-NIC injury threshold was the average peak IV-NIC at the soft tissue injury threshold.

RESULTS

The IV-NIC flexion peaks were greater than the extension peaks at all intervertebral levels, excluding C0-C1 and C1-C2 (Figure 1). The soft tissue injury threshold acceleration was found to be 8 g, as determined by significant increases above the corresponding baseline values in total NZ or ROM at C4-C5 and C6-C7 following the 8 g impact acceleration. The average IV-NIC (95% confidence interval) at the injury threshold varied among intervertebral levels, and ranged between 2.0 (1.2-2.8) at C4-C5 and 3.5 (2.4-4.6) at C7-T1, during the 8 g and 10 g impacts, respectively (Table 1). At the soft tissue injury threshold, the average peak NIC was 18.4 (17.8-19.0) m²/s².

DISCUSSION AND SUMMARY

The IV-NIC injury threshold was determined at each intervertebral level that was injured due to simulated frontal impact, using the whole human cervical spine whiplash model with muscle force replication. The many advantages of the IV-NIC over NIC in predicting soft tissue injuries include the ability to predict the intervertebral level, mode of loading, and time of injury during frontal impact. The development and validation of an injury criterion which helps predict these clinically relevant parameters is valuable in efforts to advance injury prevention measures as well as to develop better means of diagnosis and more efficient treatment.

REFERENCES


ACKNOWLEDGEMENTS

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<table>
<thead>
<tr>
<th>IV-NIC (dimensionless)</th>
<th>NIC (m²/s²)</th>
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<tbody>
<tr>
<td>C0-C1</td>
<td>4 g</td>
</tr>
<tr>
<td>C1-C2</td>
<td>6 g</td>
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<tr>
<td>C2-C3</td>
<td>8 g</td>
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<tr>
<td>C3-C4</td>
<td>10 g</td>
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Table 1. Average IV-NIC, with 95% confidence intervals, for each intervertebral level that was injured due to simulated frontal impact. The average NIC, with 95% confidence intervals, is shown in the last column for each impact.