CHILD ATD RECONSTRUCTION OF A FATAL PEDIATRIC FALL

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ABSTRACT

The current head Injury Assessment Reference Values (IARVs) for the child dummies are based in part on scaling adult and animal data and on reconstructions of real world accident scenarios. Reconstruction of well-documented accident scenarios provides critical data in the evaluation of proposed IARV values, but relatively few accidents are sufficiently documented to allow for accurate reconstructions. This reconstruction of a well-documented fatal-fall involving a 23-month old child supplies additional data for IARV assessment. The videotaped fatal-fall resulted in a frontal head impact onto a carpet-covered cement floor. The child suffered an acute right temporal parietal subdural hematoma without skull fracture. The fall dynamics were reconstructed in the laboratory and the head linear and angular accelerations were quantified using the CRABI-18 Anthropomorphic Test Device (ATD). Peak linear acceleration was 125 ± 7 g (range 114-139), HIC15 was 335 ± 115 (range 257-616), peak angular velocity was 57± 16 (Range 26-74), and peak angular acceleration was 32 ± 12 krad/s² (Range 15-56). The results of the CRABI-18 fatal fall reconstruction were consistent with the linear and rotational tolerances reported in the literature. This study investigates the usefulness of the CRABI-18 anthropomorphic testing device in forensic investigations of child head injury and aids in the evaluation of proposed IARVs for head injury.

INTRODUCTION

Defining the mechanisms of injury and the associated tolerance of the pediatric head to trauma has been the focus of a great deal of research and effort. In contrast to the multiple cadaver experimental studies of adult head trauma published in the literature, there exist only a few experimental studies of infant head injury using human pediatric cadaveric tissue [1-6]. While these few studies have been very informative, due to limitations in sample size, experimental equipment, and study objectives, current estimates of the tolerance of the pediatric head are based on relatively few pediatric cadaver data points combined with the use of scaled adult and animal data. In effort to assess and refine these tolerance estimates, a number of researchers have performed detailed accident reconstructions of well-documented injury scenarios [7-11]. The reliability of the reconstruction data are predicated on the ability to accurately reconstruct the actual accident and quantify the result in a useful injury metric(s). These resulting injury metrics can then be related to the injuries of the child and this, when combined with other reliable reconstructions, can form an important component in evaluating pediatric injury mechanisms and tolerance. Due to limitations in case identification, data collection, and resources, relatively few reconstructions of pediatric accidents have been performed. In this study, we report the results of the reconstruction of an uncharacteristically well-documented fall resulting in a fatal head injury of a 23 month old child. The case study was previously reported as case #5 by Plunkett [12].

BACKGROUND

As reported by Plunkett (2001),

A 23-month-old was playing on a plastic gym set in the garage at her home with her older brother. She had climbed the attached ladder to the top rail above the platform and was straddling the rail, with her feet 0.70 meters (28 inches) above the floor. She lost her balance and fell headfirst onto a 1-cm (⅜-inch) thick piece of plush carpet remnant covering the concrete floor. She struck the carpet first with her outstretched hands, then with the right front side of her forehead, followed by her right shoulder. Her grandmother had been watching the children play and videotaped the fall. She cried after the fall but was alert...
and talking. Her grandmother walked/carried her into the kitchen, where her mother gave her a baby analgesic with some water, which she drank. However, approximately 5 minutes later she vomited and became stuporous. EMS personnel airlifted her to a tertiary-care university hospital. A CT scan indicated a large rightsided subdural hematoma with effacement of the right lateral ventricle and minimal subfalcine herniation. (The soft tissue windows for the scan could not be located and were unavailable for review.) The hematoma was immediately evacuated. She remained comatose postoperatively, developed cerebral edema with herniation, and was removed from life support 36 hours after the fall. Bilateral retinal hemorrhage, not further described, was documented in a funduscopic examination performed 24 hours after admission. A postmortem examination confirmed the right frontal scalp impact injury. There was a small residual right subdural hematoma, a right parietal lobe contusion (secondary to the surgical intervention), and cerebral edema with cerebellar tonsillar herniation.

Also noted in the medical record was severe papilledema.

METHODS

The case study documentation consisted of the Consumer Product Safety Commission (CPSC) report form, the child’s medical and autopsy records, personal interview with the child’s mother, and the video footage of the accident. Out of respect to the family, still-frames from the videotaped fall, while used in this reconstruction will, not be reproduced in print form in this manuscript. Based on the kinematics observed in the videotaped fall, the accident was reconstructed using the CRABI-18 Anthropomorphic Test Device (ATD). The CRABI-18 was the closest match to the child’s height and weight of the modern child ATD’s common in the US (Table 1).

![Image](image.jpg)

**TABLE 1: Comparative Anthropometry**

<table>
<thead>
<tr>
<th>Child</th>
<th>CRABI-18</th>
<th>Hybrid III-3 year old</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lbs)</td>
<td>29</td>
<td>25.4</td>
</tr>
<tr>
<td>Height (inches)</td>
<td>33</td>
<td>32</td>
</tr>
</tbody>
</table>

Relying on information from the CPSC report form which was confirmed by the video documentation, an exemplar play structure was identified and purchased. Two remnants of carpet were purchased for testing: one berber style measuring 0.8-cm thick and the second was a plush pile measuring 1.1-cm thick. The ATD’s head was instrumented with three linear accelerometers (Endevco 7264C) and three angular rate sensors (Diversified Technical Systems, Inc., ARS-12K-1KCL). Data were collected at a rate of 10 kHz consistent with SAE J211 convention [13]. Angular rate data were filtered using a channel filter class 180 Hz (CFC180) and were differentiated using a five-point moving linear regression to obtain angular acceleration.

The CRABI-18 was initially positioned consistent with the child’s position and orientation just prior to the fall. The CRABI-18 was then released, resulting in a sideways rotation and fall to the carpet covered concrete floor below. Four falls onto each of the carpet surfaces were performed.

RESULTS

The exemplar play structure is shown in Figure 1. Just prior to the fall, the child was positioned straddling the side wall as shown using the CRABI-18 ATD in Figure 2. The child was initially stabilizing her position by hanging onto the posterior support column with her left hand. As she lost her balance and tipped to her right, her grip on the support column was insufficient to maintain her position and she rotated and fell to the floor below with her hands and head leading. Her right followed by her left hands were first to contact but appeared to offer little resistance to slow her body as her shoulders and elbows rotated under the load. The first substantial impact with the floor was in the right frontal parietal area followed by her anterior chest, stomach, and pelvis. The child came to rest face down on the floor. The fall sequence shown in Figure 3 is a close approximation of the child’s kinematics as observed in the video.

Results of the reconstruction are shown in Table 2. The differences between the two types of carpet were insignificant. The overall averages for HIC and peak linear acceleration were 335 and 125 g, respectively. The time window for maximizing the HIC calculation was quite short with an average of 3.7 ms.

![Figure 1: The exemplar play structure used in the accident reconstruction.](image.jpg)
This implies for these exposures, $HIC_{\text{unlimted}} = HIC_{36} = HIC_{22} = HIC_{15}$. The overall averages for peak angular velocity and peak angular acceleration were 57 rad/s and 32 krad/s$^2$, respectively.

In two of the tests, the dummy response for at least one of the metrics appears to be somewhat extraordinary. The first test of the pile carpet resulted in the largest measured angular acceleration of 56 rad/s$^2$. Based on video review of the test and the results of the other measured parameters nothing additional about the test which could help explain the relatively large angular acceleration could be identified. Similarly, the third test on the Berber carpet also resulted in an unusually high reading for HIC, a marginally higher peak linear acceleration, and an unusually low reading for peak angular velocity. Once again other than the unusual measured response, nothing from the overall kinematics could be identified to account for the measured differences.

### DISCUSSION

The CRABI series pediatric crash test devices are one of the most commonly used test devices for the assessment of pediatric head injury. The primary goal of this study was to add to the existing, but limited set of reconstruction data which are currently used for the evaluation and refinement of pediatric head injury tolerance thresholds. The current study presents a reconstruction of a uniquely well documented fall resulting in a fatal head injury of a 23-month old female.

CRABI-18 head Injury Assessment Reference Values (IARVs) of 52 g peak head acceleration and a 440 HIC are reported by Mertz [14]. In the current study the average HIC was 335 and in only one of the eight tests conducted was the response greater than 440. When Melvin [15] proposed IARVs for the CRABI-6, which predates the CRABI-18, he suggested that the primary IARV for the head be governed by the peak head acceleration, such that even if the resulting exposure

<table>
<thead>
<tr>
<th>Carpet Style</th>
<th>HIC</th>
<th>HIC window (ms)</th>
<th>Peak Linear Acceleration (g)</th>
<th>Peak Angular Velocity (rad/s)</th>
<th>Peak Angular Acceleration (krad/s$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile</td>
<td>297</td>
<td>3.5</td>
<td>126</td>
<td>61</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>324</td>
<td>4.3</td>
<td>118</td>
<td>39</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>287</td>
<td>3.4</td>
<td>125</td>
<td>68</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>304</td>
<td>3.2</td>
<td>125</td>
<td>74</td>
<td>37</td>
</tr>
<tr>
<td>Avg±Std</td>
<td>303±16</td>
<td>3.6±0.5</td>
<td>123±4</td>
<td>60±15</td>
<td>38±13</td>
</tr>
<tr>
<td>Berber</td>
<td>291</td>
<td>3.3</td>
<td>126</td>
<td>64</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>302</td>
<td>3.3</td>
<td>126</td>
<td>60</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>616</td>
<td>4.8</td>
<td>139</td>
<td>26</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>257</td>
<td>3.4</td>
<td>114</td>
<td>62</td>
<td>32</td>
</tr>
<tr>
<td>Ave±Std</td>
<td>366±167</td>
<td>3.7±0.7</td>
<td>126±10</td>
<td>53±18</td>
<td>27±8</td>
</tr>
<tr>
<td>Overall Ave±Std</td>
<td>335±115</td>
<td>3.7±0.6</td>
<td>125±7</td>
<td>57±16</td>
<td>32±11</td>
</tr>
</tbody>
</table>

**Figure 2:** The initial position of the child just prior to the fall reconstructed using the CRABI-18.

| Figure 2: The initial position of the child just prior to the fall reconstructed using the CRABI-18. |

**Figure 3:** Fall sequence reconstruction using the CRABI-18. Initially the child was stable, straddling the side wall and holding onto the posterior column with her left hand. Subsequently she lost her balance and her grip on the column resulting in a rightward rotation and fall to the floor below with hands and head leading.
TABLE 3: Summary of IARVs linked to Rotationally Induced Trauma

<table>
<thead>
<tr>
<th>Author - Study</th>
<th>Proposed Tolerance or Injury Threshold</th>
<th>Scaled Threshold based on Brain Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowenhielm 1975 [17]: numerical modeling</td>
<td>$\alpha = 4500 \text{ rad/s}^2$ and $\Delta \omega &lt; 70 \text{ rad/s}$</td>
<td>$\alpha_{\text{child}} = 5524 \text{ rad/s}^2$</td>
</tr>
<tr>
<td>Sturtz 1980 [7]: review and scaling of previously published data combined with accident reconstruction</td>
<td>Direct Head Contact – tolerance scaled for 3 yr old Pulse Duration = 10 ms $\alpha &lt; 2008 \text{ rad/s}^2$ Pulse Duration = 3 ms $\alpha &lt; 9100 \text{ rad/s}^2$</td>
<td></td>
</tr>
<tr>
<td>Ommaya 1985 [19]: review of previous studies and methods</td>
<td>For $\Delta \omega &lt; 30 \text{ rad/s}$ $\alpha &lt; 4500 \text{ rad/s}^2$: AIS 0 or 1 if $\alpha \geq 4500 \text{ rad/s}^2$ at risk for AIS 5 level injury</td>
<td>$\alpha_{\text{child}} = 5524 \text{ rad/s}^2$</td>
</tr>
<tr>
<td>For $\Delta \omega \geq 30 \text{ rad/s}$ $\alpha &lt; 1700 \text{ rad/s}^2$: AIS 2 $\alpha &lt; 3000 \text{ rad/s}^2$: AIS 3 $\alpha &lt; 3900 \text{ rad/s}^2$: AIS 4 $\alpha &lt; 4500 \text{ rad/s}^2$: AIS 5</td>
<td>$\alpha_{\text{child}} = 2086 \text{ rad/s}^2$ $\alpha_{\text{child}} = 3683 \text{ rad/s}^2$ $\alpha_{\text{child}} = 4787 \text{ rad/s}^2$ $\alpha_{\text{child}} = 5524 \text{ rad/s}^2$</td>
<td></td>
</tr>
<tr>
<td>Depreitere et al. 2006 [20]: cadaver experiments of a fall type occipital impact resulting in subdural hematoma. Combined experimental results with previous studies.</td>
<td>Pulse durations of less than 10ms $\alpha &lt; 10,000 \text{ rad/s}^2$ Longer pulse durations with $\Delta \omega \geq 40 \text{ rad/s}$ $\alpha &lt; 4,500 \text{ rad/s}^2$</td>
<td>$\alpha_{\text{child}} = 12,275 \text{ rad/s}^2$ $\alpha_{\text{child}} = 5524 \text{ rad/s}^2$</td>
</tr>
</tbody>
</table>

yields a HIC less than the HIC IARV, that the final step is to affirm that the peak head acceleration remained below the IARV for peak head linear acceleration for the entire pulse duration. Applying this rule and using the 52 g IARV reported by Mertz [14], it is clear that the IARV was exceeded in every test conducted. For this type of exposure, it appears that the limit on peak head acceleration is the more stringent of the two criteria, and in this case, also appears to be the more accurate IARV.

Currently there is not a specific skull fracture threshold associated with the CRABI-18, but the experimental results of this study indicate that the tolerance for skull fracture for a 23 month old child is likely greater than the 50% threshold value of 82 g’s and 290 HIC associated with the CRABI-6 [16].

In addition to IARV’s based in linear acceleration, many researchers have proposed limits based on rotational kinetics. The lack of skull fracture is one possible indicator that the injury in this case was due at least in part to rotationally induced trauma. Based on maturity of the child’s skull in this case, the bones were likely well fused and the overall head response was beginning to approximate the adult head response which exhibits limited deformation prior to fracture. Proposed tolerances for the head to rotational trauma are shown in Table 3. All the tolerances listed in the second column of Table 3, with the exception of those proposed by Sturtz [7], are for adults. Currently there are no generally accepted methods to scale the adult IARV’s for angular velocity, acceleration, and duration to the child due to competing reasons based on geometry and tissue properties to both scale up and down the adult thresholds [21]. Additional reconstructions such as the current study provide researchers with much needed data to be used in assessing these adult values and how they should be applied to children. Given the current lack of a validated scaling model, the adult tolerance data will be applied directly to compare the reconstruction results with the documented fatal head injury. For additional comparison, the third column of Table 3 contains scaled thresholds based on the difference in the brain mass of the adult and child. As detailed by Sturtz [7], the angular rate thresholds can be scaled for brain mass using the relation

$$\frac{\alpha}{\alpha_0} = \left(\frac{m_0}{m}\right)^{\frac{2}{3}},$$

where $\alpha$ and $\alpha_0$ are the angular accelerations and $m$ and $m_0$ are the brain masses of the child and adult respectively. Sturtz...
reports the mass of the average adult brain to be approximately 1.36 kg and the mass of the 3-year-old brain as 1.09 kg. Based on the autopsy report of this child in the current case study, the brain mass was 1.31 kg, however, the brain showed signs of extensive edema. It is much more likely, that the brain mass of the child in this case when healthy was closer to 1.0 kg. Using the relationship above and the brain masses of 1.36 kg for the adult and 1 kg for the child, the angular acceleration tolerance values in column 2 of Table 3 were scaled and are shown in column 3 of Table 3. The resulting scale factor based on the different brain masses was 1.23. Scaled thresholds for children based on brain mass alone results in values higher for children then those in adults. These brain mass scaled thresholds can be interpreted as upper limits since current studies of pediatric tissue material properties indicate that adult threshold values should be decreased to account for the tissue properties of children [21].

In all cases the average response from the accidental fall (\(\Delta \omega = 53 \text{ rad/s}, \alpha = 27,000 \text{ rad/s}^2, \text{pulse duration } \sim 4 \text{ ms} \)) exceeded the corresponding tolerances proposed for the adult and the scaled child brain. Despite some of the rather large variations from test to test within the reconstruction, applying the tolerance criteria, even on a test by test basis, still indicates the positive risk for rotational trauma induced injury for this type of fall.

One limitation of the current study is the kinematic accuracy to which the actual fall could be reconstructed. This includes reproducing the amount of fall protection the child’s arms provided, the flexibility of the hips and legs of the dummy in reproducing the slip off of the side wall, and the response of the body upon impact. Based on the video analysis of the fall it did not appear that the arms of the child provided any significant deceleration or reorientation of her body, nor were there any injuries to the child’s hands/arms recorded. If the child’s arms did provide some protection then the CRABI-18 likely over estimates the head impact severity, since the ATD’s arms did not appreciably slow the body and head prior to impact. The resistance to lateral motion of the hip joints of the CRABI-18 lies between typical passive and active joint resistance of a living child. Tighter coupling of the legs to the side wall during the slip phase may result in a more vertical orientation at impact and a slightly decreased impact velocity. The fall kinematics of the dummy and the child were compared, and this did not appear to be a hindrance in reproducing the fall kinematics in this case. Finally, one overall difference that was observed between the dummy and the child was the difference in post impact response. While the dummy’s neck and body elastically stored a portion of the impact energy and a noticeable rebound of a few inches occurred after the initial impact, the child did not appear to rebound as much upon impact. Of all the impact metrics recorded in Table 2, the rebound effect would most likely have the most influence on the head rotational velocity, resulting in increased angular velocities compared to the minimal rebound condition. Further testing with a modified neck or computational modeling would be required to answer this effect more thoroughly. A less resilient neck would appear to have a competing effect on the resulting head angular velocity. As the head becomes less coupled to the body, the angular accelerations and the angular velocities may increase for a head impact condition since the effective mass is decreasing. In contrast, decoupling the head and neck would decrease the amount of elastic impact energy stored in the neck and decrease the rebound dynamics including angular velocities. It should be noted that in this case study, the angular velocities are well above all of the proposed thresholds in Table 3 (with the exception of the 70 rad/s of Lowenhelm 1975 which the author later revised down to 30 rad/s based on subsequent work in 1978). Thus, only a change in ATD design that yields a dramatic change in angular velocity would affect the results of this case study.

CONCLUSIONS

The results of this reconstruction are consistent with the current injury criteria based on both linear and angular acceleration. The CRABI-18 test device is an important tool in the assessment and evaluation of injury prevention and forensic investigation. This study further underscores the efficacy of this device.

REFERENCES


