

Child Head Injury Evaluation Using Crash Dummy Head Finite Element Model

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Abstract

In this work, the responses of child head to impact with a rigid surface have been investigated for five impact locations using finite element analysis. The Three Year Old (3YO) head model used was first validated by comparison with cadaver experimental data of size matched Nine Year Old (9YO) child head reported in the literature. The head model is comparable to 9YO cadaver in peak acceleration with highest difference of 29% in forehead; other impact locations were within 10% difference. Simulation was carried out in LS DYNA finite element code at 150mm and 300mm drop heights and Head Injury Criteria in 15 millisecond interval (HIC15) and Von Mises stress were found to be high for high impact heights. Occiput experienced highest HIC15 for the two heights. HIC15 for all impact locations and drop heights were found to be below the threshold of 570 for 3YO, recommended by National Highway Traffic Safety Administration (NHTSA). Von Mises stress was also different for impact locations and the highest value of 1.88 MPa at 300 mm height was found for frontal impact. This study revealed the variation in injuries for various crash dummy head locations for vehicle interior, helmet, and child restraint seat and vehicle front structure design. The results informed vehicle designers the extent of protection needed at various head impact locations. The head model can be applied in child safety assessment for vehicles and playgrounds.

Keywords

Crash Dummy Head, Finite Element Analysis, Head Impact Location, Head Injury Criteria

1. Introduction

Traumatic brain injury is a significant global health concern, causing millions of

cases of hospitalization, death, and disability each year, with an estimated 27 - 69 million people affected worldwide annually [1]. Child vehicle occupants remain one of the most vulnerable groups in road traffic environments due to their unique anatomical and biomechanical characteristics compared with adults; children possess softer cranial bones, higher head-to-body ratios, which increase susceptibility to head injury during vehicle crashes or secondary impacts. Understanding the mechanisms of child head injury is therefore essential for improving restraint system design, vehicle interiors, and impact mitigation strategies.

Crash test dummies, particularly child Anthropomorphic Test Devices (ATDs), play a critical role in evaluating head injury risk. However, traditional ATDs are limited by simplified geometry and material properties that do not fully capture the complex, age-specific responses of a child's head during dynamic loading. The Finite Element Method has emerged as a crucial tool for investigating injuries, providing a cost-effective and ethical alternative to physical testing [1]. Chen [2] studied the child human head finite element model in head drop simulation, the peak impact accelerations were found to be different for frontal, left parietal, occipital, right parietal and vertex locations. Loyd *et al.* [3] investigated the response of cadaver heads for various impact locations for children and adults and compared it with ATDs. Differences were discovered and multipliers were suggested for correcting the dummies for better biofidelity. Sahari *et al.* [4] investigated the responses of 1YO, 3YO and 6YO child crash dummy head on falling on rigid floor and found that HIC15 depends on age, drop height and angle of impact. Studies reported validated head models only for frontal and side impacts but very few studies reported crash dummy head that measures impact for various locations [5]. Vehicle protective devices and vehicle structure designers often consider the various locations with same injury likelihood.

The aim of this study is to compare the 3YO crash dummy model with cadaver response with the aim of determining its biofidelity and also to present a computational investigation of a child crash dummy head finite element model subjected to multiple impact locations by analyzing biomechanical metrics across frontal, lateral, vertex and occiput impacts. The study aims to advance scientific understanding of pediatric head injury mechanics and contribute evidence-based insights for improving child safety systems in transportation and non-transportation environments. The HIC15 and Von Mises stress of various head locations were studied with the aim of determining the injury severity using ATD finite element head model which is more simplified and available than human head model so as to provide information to designers in coming up with relevant safety designs. However, only head is used in the present work, torso and limbs were not included.

2. Materials and Methods

2.1. Crash Dummy Head Model

The 3YO dummy head model used in this study was scaled from six year old crash

dummy shown in **Figure 1** [6].

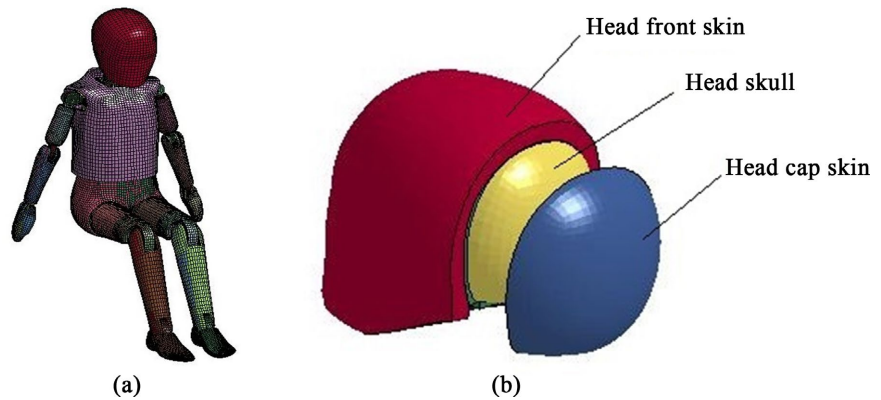


Figure 1. 6YO child crash dummy model (a) and head finite element model (b).

Morphing technique was applied to scale 6YO dummy head to 3YO head anthropometry. Scaling factors were calculated for head height, head breadth, and head depth in x, y, and z directions: λ_x , λ_y , and λ_z as the ratio of base line length to the destination length. Now the scaled model, x is given as:

$$x_{scaled} = R x_{original} \quad (1)$$

where R is the transformation matrix. **Table 1** shows the scaling factors used.

Table 1. Factors used for scaling 6YO HIII dummy head model to 3YO anthropometry.

Description	6YO HIII (Measured)	3YO child dimension [7]	Scaling factors
Head height (cm)	14.8	13.7	0.93
Head breadth (cm)	14.6	13.4	0.92
Head depth (cm)	17.2	17.4	1.01

Morphing was done in LS-PrePost by constraining the parts to be morphed (Morph nodes) within a solid hex mesh (Constraining Element). The nodal coordinates are transformed appropriately according to their relative position within their constraining solid element as shown in **Figure 2**. This scaling procedure was applied in previous studies [7] [8].

The materials properties of the dummy head and impacting plate are shown in **Table 2**.

2.2. Simulation Setup

The head model was removed from the dummy model for the impact test in accordance with crash dummy head drop test procedure [6]. Head drop test was conducted in LS DYNA code. Surface to surface contact with a friction coefficient of 0.2 as suggested by Li *et al.* [10] is defined between head and rigid plate. Hour-glass energy was set to be 10% of the total energy. For frontal impact, the head was tilted so that z-axis form an angle of 28.5° with horizontal while the mid

sagittal plane is vertical and for lateral impact the mid sagittal plane was tilted to make 35° with impact surface from the top of the head [11]. For vertex and occipital impacts, the head was oriented such that the mid sagittal plane is 90° to the impacting surface. **Figure 3** shows the positioning angles, impact locations

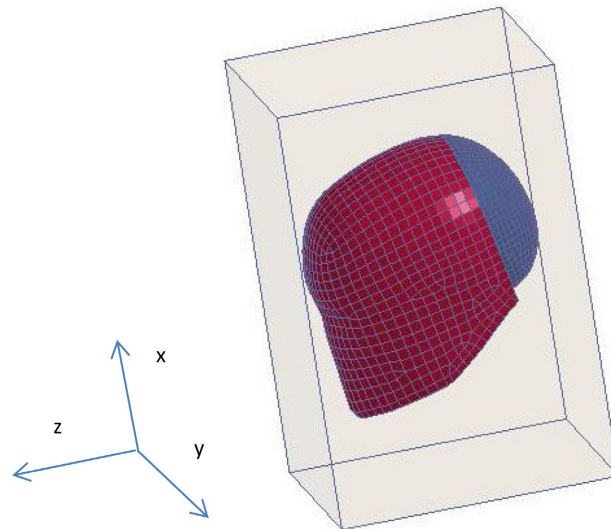


Figure 2. Morphing of 6YO dummy head to 3YO anthropometry.

Table 2. Crash dummy head materials properties [5] [9].

Head component	Material model	Parameters						
		E (MPa)	ρ (Kg/m ³) 10 ³	K (MPa)	G_o (MPa)	G_l (MPa)	ν	β (1/Sec)
Head front and cap skin	Linear viscoelastic	NA	1.2	2	0.25	0.08	NA	250
Skull (Front/Cap)	Rigid	4700	1.8	NA	0.2	NA	0.2	NA
Impacting plate	Rigid	2.07×10^5	7.85	NA	0.3	NA	0.3	NA

ρ : mass density, E : Elastic Modulus, K : Bulk Modulus, ν : Poisson's Ratio, G_o : Short Term Shear Modulus, G_l : Long Term Shear Modulus, β : decay constant.

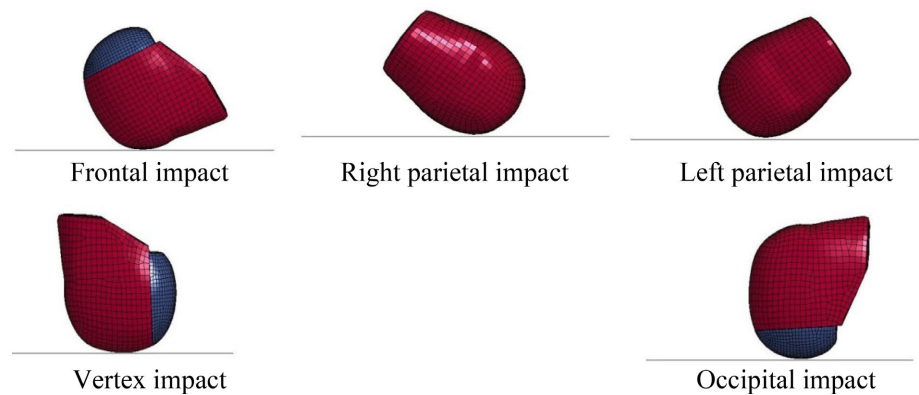


Figure 3. Head drop test orientation for five impact locations.

and simulation set up. The 3YO crash dummy head model has an element size that is computationally stable and economical for which calculation takes only 9 minutes to complete.

Impact velocities were calculated based on the drop height between head and impact plate according to the relation:

$$v = \sqrt{2gh} \quad (2)$$

where h is the height of fall and g is gravitational acceleration.

The height of 150 mm was selected based on the distance between child head and child restraint seat or side door beams while 300 mm considered the frontal impact of child head with vehicle interior and pedestrian impact distances. This study didn't cover higher drop heights which may lead to fracture of skull and other human tissues and this is beyond the capability of the crash dummy head model.

Peak resultant acceleration describes the peak magnitude of translational acceleration felt by the center of mass of the dummy head during impact. The resultant acceleration of the dummy model was measured by accelerometer located at the head center of mass which provides the components of acceleration in x , y , and z directions and the resultant acceleration is evaluated as [1]:

$$a_{result.} = \sqrt{(a_x^2 + a_y^2 + a_z^2)} \quad (3)$$

HIC is the main criteria used in assessing the head injury risk on impact. It is the standardized maximum integral of head acceleration measured at the center of mass within a specified time windows. It is calculated based on the equation [12]:

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a_{result.} \cdot dt \right]^{2.5} \cdot (t_2 - t_1) \quad (4)$$

Where t_1 and t_2 are the initial and final times of intervals within which HIC reaches a maximum value. Acceleration is measured in unit of acceleration of gravity (g) and time in seconds. The ISO time recommended limits of 15 ms (HIC15) was used in this study. HIC15 was calculated within 10 ms simulation time because the peak acceleration was captured within this timeframe.

Von Mises stress is a crucial criterion in finite element modeling of soft tissue, assessing structural integrity and failure risk. It provides a scalar value combining stress components, predicting deformation or failure under external forces. By comparing calculated stress to a yield point, potential failure points and injury mechanisms in soft tissues can be determined. Von Mises stress- time graphs were recorded from the simulation results for the two drop heights and five impact locations.

3. Results and Discussions

3.1. Head Model Validation

The head model was validated against the available 9YO cadaver head peak accel-

eration reported by Loyd [13]. Head depth, height and circumference of 9YO cadaver used for the validation are 16.9 cm, 13 cm and 49.3 cm and drop mass was 2.17 kg [3] which is close to 18 cm-head depth, 13.5 cm-head height and 48.4 cm-head circumference and 2.02 kg-drop mass for 3YO [14]. It can be seen in **Table 3** that the peak acceleration differs especially for frontal impact and this can be due to biomechanical differences of the 9YO child compared to 3YO. Though nine years old skull is more rigid and its tissue material properties differ from 3YO, the difference is acceptable due to scarcity of age matched cadaver data. It is also better than using adult scaled data. In addition, crash dummies are simplified models that may not capture variability in cadaver age and embalming. Mesh size and differences in geometry may also cause the response differences.

Except for left parietal and vertex locations, head acceleration is lower for 3YO than 9YO cadaver which explains the biomechanical differences between the two heads compared. The percentage difference in **Table 3** is within 10% for all impact locations with the exception of front which might be due to age differences and characteristics of the dummy head. It should be noted that drop heights for all impact locations are approximated to 150 mm and 300mm in the comparison shown in **Table 3**.

Table 3. 3YO head model comparison with 9YO cadaver data.

Impact location	Drop height (mm)	Impact velocity mm/sec	9YO child cadaver head peak resultant acceleration (g) (Loyd, 2011)	Peak Resultant acceleration of 3YO dummy model (g)	Difference (%)
Forehead	302	2434	146.3	112.9	29.4
Left parietal	300	2426	123.3	129.4	4.7
Right parietal	302	2434	142.5	132.4	-7.6
Vertex	299	2422	130.8	139.4	6.2
Occipital	302	2434	150.8	145.2	-3.9

3.2. Head Drop Test Results

Figure 4 shows a typical dummy model HIC15 for 150 mm drop height (1721 m/s impact velocity) for frontal test. The HIC15 is 239 as calculated by LS DYNA finite element code. Detail results for other impact locations and drop heights are presented in **Table 4**.

The Von-Mises stress which defines how head impact with vehicle structure affect the head tissue is an important parameter in determining bone fracture and deformation. The result for 150 mm drop height (1721 m/s impact velocity) is presented in **Figure 5** with peak value of 1.29 MPa in 0.01 s simulation period.

Von Mises stress occurs at the impact point with rigid floor. Maximum Von Mises stress is obtained at 0.006 sec. **Figure 6** shows the contour plot for Von Mises stress from 0 sec to 0.0075 sec.

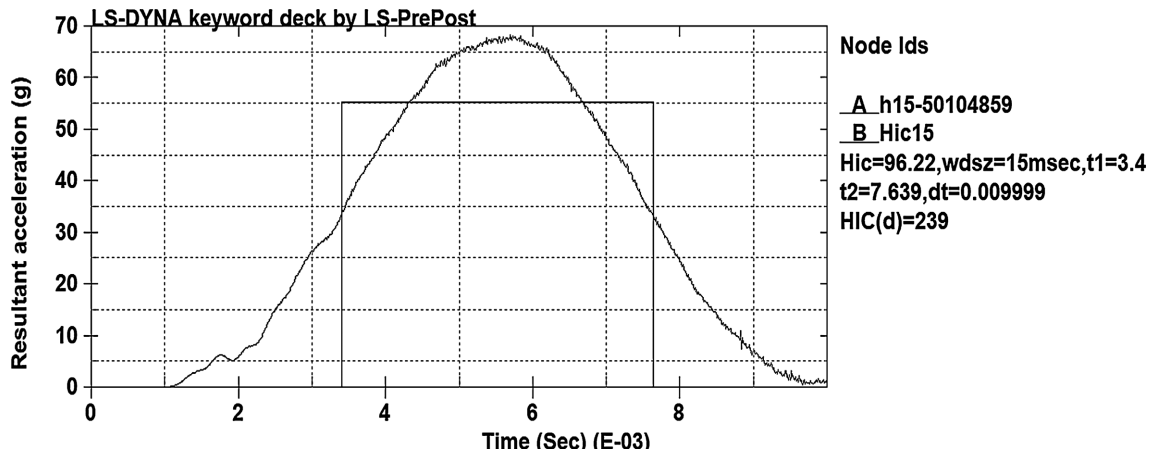


Figure 4. HIC15 of crash dummy head at 150 mm drop height.

Table 4. 3YO head model HIC15 and maximum Von Mises stress for five impact locations.

Drop height		Frontal	Right parietal	Left parietal	Occiput	Vertex
150 mm	HIC15	239.0	257.0	272.7	285.4	270.8
	Maximum Von mises stress (MPa)	1.29	0.71	0.91	0.81	0.51
300 mm	HIC15	388.9	427.0	411.8	530.5	468.7
	Maximum Von mises stress (MPa)	1.88	1.06	0.93	1.34	0.93

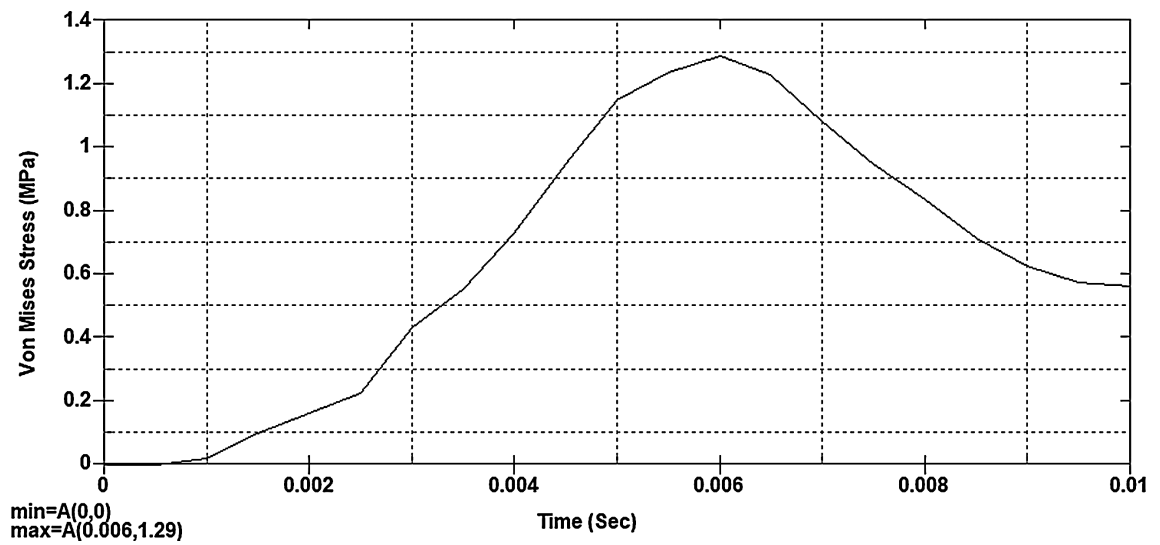


Figure 5. Von Misses stress of crash dummy head at 150mm drop height.

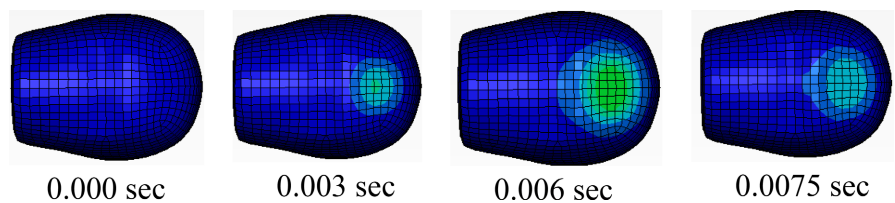


Figure 6. Von Misses stress profile at some instances of the simulation.

Comparison of HIC15 for two drop heights with impact locations is shown in **Figure 7**. HIC15 values are generally higher for 300 mm drop height (2426 m/s impact speed) than 150 mm drop height (1721 m/s impact speed) for all impact locations; this is expected because the impact force which results in higher accelerations is high at high speed. HIC15 values are below the minimum acceptable value of 570 for 3YO. This means at these impact velocities the 3YO child would be safe even if the surface is rigid. High decelerations in vehicle crash results in high impact forces. HIC15 of 239 for 150 mm drop height in frontal impact is consistent to pediatric results reported by Loyd *et al.* [3]. Occiput experienced highest HIC15 than other locations with 530.5 for 300 drop height which is below the threshold of 570 for 3YO. This shows that the child seat head restraint should be able to absorb impact energy to reduce such high HIC15. 3YO Hybrid III dummy experienced high HIC15 at occiput in the results reported by Loyd [13]. Occiput was also reported to have highest peak acceleration in the work of Chen [2]. Occiput impact is as a result of rear impact due to whiplash. Vertex location experienced high HIC15 of about 480 which is in par with what was reported in the literature [13]. Impact on vertex is usually found in vehicle rollover or in child fall and it can be protected with helmet in bicycle or sports. Thus, the design of such helmets in the vertex should consider the high HIC15 in that direction. Right and left parietals experienced close HIC15 values at the two velocities and this is attributable to symmetrical nature of crash dummy head model and this is in line with cadaver and crash dummy head results reported by Loyd [13].

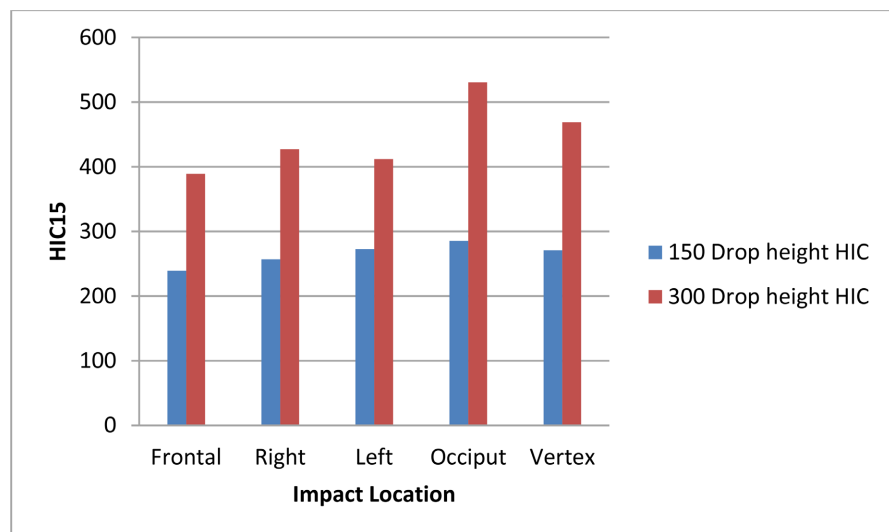


Figure 7. HIC15 of dummy head for the impact locations.

Maximum Von Mises stress is another parameter used to evaluate the injury severity at tissue level. Forehead experienced the highest stress than other locations as shown in **Figure 8**, though it has lowest HIC15 as shown in **Figure 7** at the two drop heights. This is because HIC15 and von misses stress are different injury mechanisms. HIC15 measures injury risk based on linear acceleration and

duration while von mises stress indicates localized material yielding. High stress can be attributed to dummy characteristics due to simplified skull construction which makes the front location to be stiffer than other impact locations. Left parietal shows close values of Von Mises stress at the two drop heights which might be due to symmetry and other dummy characteristics. The Von Mises stress ranges between 0.51 MPa to 1.88 Mpa. The lowest is found at vertex for the two heights. High heights experienced high Von-mises stress as expected because at higher drop height the impact energy is high which results in high stresses at the impact point. Von mises stress increase with height but is not consistent with HIC15 in particular head location because HIC15 measures kinematics of head excursion while Von-mises stress measures impact due to contact of material with rigid surface. Viscoelastic material properties of dummy head can predict Von Mises stress experienced by child head on impact hence could be used in safety assessment of vehicle.

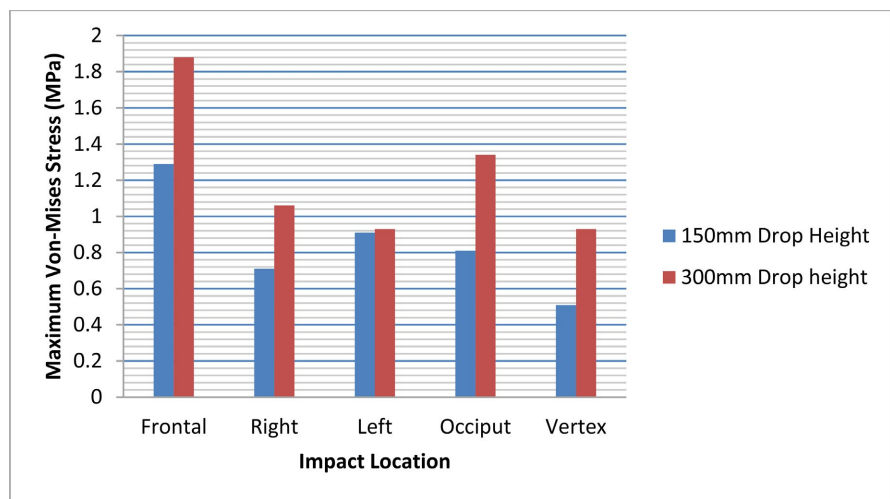


Figure 8. Von Mises stress of dummy head for the impact locations.

4. Conclusions

The responses of the head model used in the simulation were comparable to that of 9YO cadaver hence validating the model for five impact locations due to scarcity of three years old child cadaver data. Crash dummies could therefore be modified to assess impact for different locations. HIC15 of 3YO child head depends on the impact velocity and injury parameters were found to be different for various impact locations. Therefore, in the injury evaluation of protective devices, impact location is crucial. Stresses were generated on head impact and increased with impact heights. Impacts at various locations require different protection. High HIC15 means critical need for enhanced head-restraint interaction in child seats. Designers need to enhance design with energy absorption form. High Von Mises stress for front location provides biomechanical basis to designers on the need to use liners with lower initial stiffness for pediatric helmet.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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