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Injury biomechanics for aiding in the diagnosis of abusive head trauma

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The neurosurgeon caring for the potentially abused infant or child is asked to look at the injuries and determine what happened, when it occurred, and if the provided history is consistent with the findings. Unlike most injury scenarios, where the patient presents with a known cause of injury, the history given for an infant or child who has suffered from inflicted trauma contains little or no true information about what actually occurred. The stated cause is often deceptive, but may contain elements of the truth that make the story seem more plausible. In some cases, the person bringing the child for care may be unaware that an injury has even occurred, but seeks care because of concerns about the infant's symptoms, such as vomiting, increased sleeping, or irritability. Because accidental and abusive trauma can present similarly, it is imperative that the physician caring for the head-injured infant consider the stated mechanism and all of the clinical findings before reaching any conclusions as to cause. If the injury type and severity do not match the expected injury potential of the stated cause, additional information should be sought to better define the extent of injury and the details of how this occurred. Because the true mechanism of injury is rarely known in abuse cases, the physician must use all available information to determine best the manner of injury. The story is to be reconstructed from the physical findings, clinical presentation, and time course of the patient. Diagnosing abuse in the young child or infant requires piecing together a puzzle of facts without assumptions.

A missed diagnosis of abusive head trauma can be catastrophic because the young infant or child who is being abused has a very high likelihood of suffering further insult that may result in morbidity and even mortality [1–4]. Equal in harm to the family and the child is when a truly accidental head injury is diagnosed as an abusive event. Careful and expert consideration is required to decrease the likelihood of either accusing innocent families of abuse, or misdiagnosing a child who has suffered abusive trauma, placing the patient back into a potentially harmful environment. To improve accuracy and expert opinion concerning the manner and timing of the injury, a biomechanical approach is the key. An understanding of the biomechanics of specific injuries and specific injury mechanisms provides a more objective approach for evaluating consistency between the stated cause of injury and the actual clinical findings. This understanding may also help guide therapy, interventions, and anticipation of the potential for neurologic deterioration. A biomechanical profile for evaluating head injuries in young infants has been outlined by Duhaime et al [5] and Hymel et al [6] has proposed a biomechanical approach for assessing potential abusive head trauma.

Inconsistency between the history and observed injuries is one of the red flags used to differentiate accidental and nonaccidental head trauma

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(i.e., a minor history accompanied by major or multiple injuries). In some cases this discrepancy may be based on learned assumptions rather than experience and medical reason. It is critical to keep an open mind to the injury potential for various mechanisms, while gathering more data in a nonaccusatory manner. A biomechanical approach to evaluating the head-injured patient can provide a more scientific and objective framework for diagnosing a discrepancy between history and injury. Evaluating this inconsistency and determining that a head injury is or is not consistent with the stated history requires (1) an understanding of what types of biomechanical forces are necessary to result in specific types of head injuries, (2) what the mechanical injury potential is from the reported cause, and (3) what the expected clinical presentation and course are for a given mechanism and resultant injury. These key areas are the focus of this article, which provides an overview of concepts in injury biomechanics as they pertain to the clinical evaluation of an infant or young child who may have an inflicted head injury, and reviews experimental modeling of head injury. The reader is referred elsewhere for further information [7–10,95].

Evaluating the potentially abused infant or child

The physician must begin by obtaining a detailed history of the event and carefully defining all the cranial and noncranial injuries. A detailed history of the event with a focus on the biomechanical explanation of the cranial injury is essential. The history should be taken with sufficient detail to allow for biomechanical reconstruction of the incident. If the historian reports, for example, that the child fell down a flight of stairs, it is essential to ask how many steps, of what the steps are made, and on what type of surface the child landed. It is also important that the history is taken before providing the historians with any information about the patient's injuries. Documentation of the initial history is also important because in abusive trauma, the history often changes as the perpetrator learns more about the injuries and begins to fabricate a more realistic history of the event. The physician must next define the cranial injuries and then classify them as either primary or secondary. Although the presence of secondary injury has a profound effect on treatment and outcome, only the primary cranial injuries can be explained by biomechanics. If the patient requires an operative procedure, the operating room is the place where the neurosurgeon is able to add a unique perspective to the biomechanical puzzle. In some cases of abusive injury, the only evidence of impact is that seen by the neurosurgeon in the operating room. In addition, the presence of new or old blood, and xanthochromia in the hemorrhage may provide important clues to the timing of the injury event.

To determine plausibility of a given set of injuries resulting from a stated cause, all of the injuries must be identified and taken into consideration. Can a single event explain all of the medical findings including time course of clinical presentation? Key aspects for consideration when evaluating the injury potential of a given mechanism are whether the stated cause generated sufficient energy to cause all of the discovered injuries, and whether the types of injuries match the biomechanics of the event.

Biomechanics of specific types of head injuries and other injuries commonly encountered in abuse

Brain injury can be caused both by forces directly applied to the brain and through indirect forces transmitted to the head through the neck. The primary head injuries from contact forces occur at impact. Contact forces cause focal injuries but are not the cause of diffuse brain injuries, such as a concussion [7]. Indirect forces, or inertial accelerations, are typically applied to body regions (e.g., torso) other than the head and often result in a whiplashing effect. Accelerations may be linear, rotational, or a combination of the two. Both direct and indirect forces applied to the head can result in accelerations, or changes in velocity, which lead to stress or strain within the brain. Gennarelli and Thibault [7] note that "strain is best understood as the amount of deformation that the tissue undergoes as a result of mechanical loading," and because "biological tissues are viscoelastic, their tolerance to strain changes with the rate at which the mechanical load is applied." Melvin et al [11] summarized the various mechanisms of brain injury as follows: (1) direct contusion from skull deformation, (2) brain contusion from motion relative to the internal skull surface, (3) reduced blood flow caused by pressure or infarction, (4) indirect contusion of the brain opposite the side of impact, (5) tissue strain produced by relative motion of the brain with respect to the skull or hemisphere, and (6) rupture or tearing of the blood vessels between the brain and dura mater.

External abrasions and contusions

Scalp and face findings add an important piece to assessing the plausibility of a given mechanism and provide information concerning contact forces or phenomena. Scalp abrasions, swelling, and bruising result from direct contact forces and should be identified and documented before any surgical interventions. The absence of scalp and subgaleal swelling does not preclude impact, and in some instances no impact can be found [12, 13]. A soft surface may dissipate the force of impact to the head, resulting in brain injury without visible signs of trauma [14,15]. In a study by Duhaime et al [14], all patients who died from abusive head trauma had evidence of blunt head trauma, but in several of the cases evidence of impact was found only at autopsy on reflection of the scalp. It is also important to document the number of planes the bruising reflects (i.e., forehead and back represent two different directions of impact force). Does the reported mechanism account for multiple directions of force or is the described event more unidirectional? Bruising about the ear or pinna is a relatively common finding in severely injured children where abusive trauma is the cause. This can be an important observation not only for helping validate or refute the history of injury, but for evaluating potential injuries associated with ear bruising, such as described by Hanigan et al [16]. The constellation of unilateral ear bruising, ipsilateral cerebral edema, and hemorrhagic retinopathy is described as the tin ear syndrome. Hanigan et al [16] hypothesize that the rotational acceleration produced by blunt trauma to the ear produces these findings. In their report, all of the children with these findings had poor outcomes. Bruising of the ear can be an important indicator of a more serious intracranial process [16]. Likewise, the presence of a subgaleal hematoma often indicates a skull fracture is present [17,18]. Bruising and abrasions elsewhere on the body should also be documented. These findings reflect points of contact and are helpful for injury reconstruction, biomechanical consideration of the event, and assessing the plausibility of the history. Soft tissue findings may also point to other, occult or nonobvious injuries.

Skull fractures

Skull fractures result from impact, or direct contact forces when energy is absorbed and injury threshold is exceeded. Local inbending of the skull occurs with impact. This results in compression and tension strains on the inner and outer tables, respectively. The fractures begin in the inner table and take the path of least resistance. It is the thickness of the skull that determines fracture propagation length and direction [7,19]. Linear fractures result from a broader contact force, such as a floor, whereas depressed skull fractures result from a smaller, more focused impacting energy, such as the edge of a coffee table, or a small object, such as a hammer. Basilar fractures result from propagated stress waves [7]. Aging of skull fractures is difficult, but the presence of soft tissue swelling clinically or by CT may help indicate that the injury is acute [18]. Fractures of the skull occur in both accidental and abusive trauma. To help with differentiation, several papers have studied specific characteristics of skull fractures resulting from accidental versus abusive trauma. Multiple fractures, bilateral fractures, and fractures crossing sutures were more commonly associated with abuse cases [20]. The parietal or occipital bones were the site most often involved in abuse cases [21,22] and a depressed occipital fracture was found to be highly suspicious for abuse [23]. Simple linear fractures can occur from short distance falls, and are common in both accidental and abusive trauma [24]. Most of the fractures in Duhaime's et al [14] study on shaken baby syndrome were in the occipital or parieto-occipital region and "more complex injuries were associated with greater mechanical impact forces generated from higher falls" [5].

Cerebral contusions

Cerebral contusions are the result of direct contact forces and can occur directly beneath the site of impact, or away from the site of impact (contra coup) as a result of propagated energy [25]. The injuries are focal and occur most commonly in the frontal and temporal poles and on the inferior surfaces because of bony prominences. Gliding contusions are focal hemorrhages in the cortex and subjacent white matter. They are believed to result from acceleration-deceleration forces and are a common finding in cases of diffuse axonal injury (DAI) [25]. Contusions and subarachnoid hemorrhages are also seen from inflicted head injury, as identified by MRI [5]. In accidental cases, focal contusions are found in "more significant falls resulting in focal parenchymal contusions or focal subarachnoid hemorrhages." Of interest, those children whose injuries resulted from accidental trauma did well clinically in general [5].

Subdural hematomas

Subdural hematoma (SDH) "is the most common and distinctive type of central nervous system injury detected on imaging studies in abuse" and in cases of inflicted head injury, occur more commonly in the occipital region and posterior interhemispheric fissure [3,5,17,26]. A subdural can occur from contact forces with resultant subdural bleeding occurring directly underneath the impact site. Epidurals, uncommon in child abuse, also occur from contact forces directly under site of impact, and are often associated with a skull fracture. Epidurals, and some subdurals resulting from direct contact, are associated with good clinical outcomes if diagnosed before secondary brain injury [27]. Most SDHs, however, occur from inertial or indirect angular acceleration-deceleration forces [28] that cause disruption of bridging veins or other surface vessels. Bridging veins are sensitive to high strain rate conditions; "SDH result from high-strain accelerations that produce short duration, high strain rate loading" [7,29]. With rapid angular deceleration of the head, the brain continues to rotate in relation to the skull and dura, resulting in strain forces on surface vessels. Once threshold is exceeded, tearing and resultant SDH occur. Depending on magnitude, rate, and duration of the acceleration-deceleration forces, injury threshold for diffuse brain injury may also be met [5,7,30]. In fact, SDHs have a high association with bad outcomes in traumatic brain injury victims. This morbidity and mortality association is caused in part by injury to cerebral parenchyma from the same acceleration-deceleration forces that caused the SDH [31].

Primary diffuse brain injury

"Concussion is the beginning of the clinically apparent continuum of primary diffuse brain injury" [6] and loss of consciousness at the time of injury is an indicator of primary diffuse brain injury [6,32]. Forces applied to the head that result in rotation of the brain cause diffuse brain injuries, and at the moment of impact, diffuse damage to the white matter can occur [7,15,32,33]. Contact forces do not directly cause diffuse brain injury [7], although the contact strains may set the head in motion, resulting in acceleration-deceleration forces sufficient to cause diffuse brain injury [7,25]. Concussions and DAI are caused by inertial or acceleration-deceleration forces injurious to the brain parenchyma by producing strains within the brain tissue. The acceleration loading causes sufficient strains within the brain so that the brain tissue itself is injured [7]. When the patient is severally or fatally injured, nerve fibers in the white matter are torn at the time of the impact [33,34]. Direction of acceleration and impact occurrence are important variables affecting injury potential. Greater damage occurrs in animal models with movement in the coronal plane, or lateral head motion [35]. Duhaime's et al [14,15] model of a shaken infant showed that the magnitude of angular deceleration is 50 times greater with impact. Angular acceleration forces, when associated with impact, reach calculated injury threshold for SDH, concussion, and DAI.

In the infant with brain injury, it is important to determine if the infant lost consciousness at the time of the injury, and if so, for how long. If the mechanism from history is more translational in force production, such as a short distance fall, and yet the injuries are consistent with angular acceleration (i.e., SDH, loss of consciousness, or DAI) further investigation is critical. Did the fall generate greater biomechanical forces than assumed or expected, or are there additional findings inconsistent with accidental trauma?

Secondary injury and brain edema

The causes of brain swelling are not always clear, but can occur secondary to the primary insult. Swelling may be focal, unilateral, or diffuse [9,25]. Focal swelling is typically adjacent to a contusion as a result of direct impact injury; unilateral cerebral edema usually occurs in association with an ipsilateral SDH [25]. Diffuse swelling can result from diffuse structural damage or increased cerebral blood flow, or swelling can be a reflection of the added injury of hypoxia and ischemia. The precise cause of cerebral edema in any given case is not always clear, and in abusive head trauma multiple mechanisms may coexist. Swelling can occur immediately after major blunt force trauma, or soon after when significant brain injury has occurred [36,37]. Brain swelling may also take several hours or days to evolve, adding to the challenge of patient management and injury diagnosis.

In the severely injured child, apnea, hypoxia, and ischemia are often present, and contribute to the deleterious effects of the initial insult. The role of hypoxia and ischemia in causing severe brain swelling is especially important to consider when an infant has been harmed as a result of a violent outburst. It is not uncommon for medical attention to be sought only after the caretakers fear the child has died, or after someone else comes onto the scene or into the home, initiating an emergency response call. This can delay care for hours, or possibly even days, thereby worsening secondary injury.

Other organ systems injured

In the infant presenting with a head injury, other systems should also be evaluated for injury. Liver or spleen bruising or lacerations and bony injuries, such as rib, metaphyseal, and long bone fractures, are relatively common findings in the battered infant with a brain injury. It is important to identify all injuries for the well-being of the patient and for consideration of the mechanism and the expected injury potential. The absence of any other injuries can also provide helpful information for evaluating the consistency between the stated cause and the clinical findings. Additional radiologic testing to detect additional occult, extracranial injuries should be performed in any child less than 2 years of age, any child who is developmentally delayed and cannot reveal a history of abuse, and any child who is comatose [38]. Findings on a skeletal survey can add important biomechanical information [5] about the injury including the point of impact, the force with which the impact occurred, and the direction of impact. A skeletal survey can also reveal the presence of previous, unreported trauma. Laboratory evaluation can often add additional evidence. The presence of increased liver or pancreatic enzymes in a patient without a history of hypoxia or hypotension suggests abdominal trauma [39,40] even in the presence of a normal abdominal CT scan. Injuries to the pancreas, retroperitoneal duodenum, and liver and spleen occur with forceful, concentrated direct blows to the epigastrim. When this constellation of injuries is discovered, abuse must be strongly considered. Other sites of injury add an important element when considering feasibility of a mechanism causing a specific injury or set of injuries.

Subtle or occult injuries of forensic significance

Injuries are often defined by whether or not they require intervention. Such injuries as a bruise on a cheek [41,42] or an abrasion on an arm have little consequence for treatment or outcome in accidental trauma and are rarely even considered in the list of significant injuries after trauma. When the cause of injury is unknown, unclear, or abusive, however, defining injuries becomes a staged procedure in which injuries are defined as any change in the normal structure of the body at a clinical, radiographic, intraoperative, or pathologic-histologic level. Even mild laboratory abnormalities need to be considered injuries even if they do not warrant intervention.

When trying to identify cases of abuse and prevent wrongful accusations in cases of truly accidental injury, gathering as much information as is possible is critical. These findings may have no actual clinical or operative significance, but may be pivotal in differentiating abusive from nonabusive trauma.

Prior injuries

There may be multiple injury events when a child is in an abusive environment, and prior injuries may have occurred when infants and young children present with abusive head trauma. In Ewing-Cobbs et al [3], almost half of children with abusive head trauma had evidence of prior undiagnosed head injury on CT scan compared with none of the children with accidental injury. The affect of prior head injury as it relates to a new head injury is unclear but the possibility is raised that the biomechanics of repeat injury are different. Old injuries raise concerns for the child's future safety and may point to an ongoing, abusive environment. Each prior injury and its reported cause must also be considered when evaluating the current injury and mechanism.

Mechanical injury potential of common injury events and clinical observations

To differentiate between abuse and nonabusive head trauma, it is necessary to have an understanding of the biomechanics of mechanism and injury potential of injury where the cause is not abuse. One of the most common described mechanisms of injury in abuse cases is a fall, such as a fall from a couch, bed, or crib, or a fall down stairs. There is a vast body of literature addressing the topic of injuries from fall, associated injuries and mechanisms, and the expected injury potential of a given mechanism. An understanding of the biomechanics of accidental falls aids the neurosurgeon in evaluating the expected injury potential of a given history. This section highlights some of these articles on injury mechanism, and the clinical and experimental outcomes.

In part, the laws of physics govern the types of injury occurring in free falls. Heights of fall and material properties of the impact surface are the primary factors influencing free-fall injury severity. The fall victim's weight and impact landing position are also key to predicting free-fall outcome. The height of a free fall plays a key role in the injury outcome. Impact force, which is a function of body mass, fall height, and stopping distance, also is a critical factor in resultant free-fall injuries. Stopping distance is largely a function of impact surface properties. In particular the stiffness or energy absorbency of the surface influences stopping distance. Impacting on a soft surface, such as mud, results in a change in velocity over a longer period of time, which reduces the level of deceleration to what the falling body is exposed. Conversely, falling onto a stiff, rigid surface, such as concrete, results in a shorter stopping distance and ultimately a higher level of deceleration. Higher levels of deceleration are translated into greater injury severity. Impact energy, which is directly related to body mass and impact velocity, is also a factor influencing free-fall outcome. The distribution of impact force may also play a key role in free-fall injury. Forces that are distributed over a larger portion of the body, as opposed to a concentrated region, serve to diminish impact force in a fall.

Falls are one of the most common causes of traumatic death in children under the age of 15 years [43]. Based on a 1986 study of children who were hospitalized because of brain injury in San Diego County, California, it is estimated that nearly 30% of childhood injury deaths resulted from head injury. An estimated 34,100 children age 0 to 4 years in the United States suffered traumatic brain injury. Of these, half were related to falls [44]. This high incidence of falls was also confirmed as the primary cause of injury in children age 0 to 12 years [45]. In the study by Gallagher et al [45], falls were also found to be responsible for the greatest proportion of head injuries in all children. Krauss et al [44] reported in a 1990 study that 56% of serious brain injuries in children younger than 1 year were associated with abuse. Billmire and Myers [24] found that 36% of head injuries were associated with abuse in infants 11 months and younger. Chadwick et al [46] examined fatal outcome of injury in 317 infants and children who presented with a history of having fallen. Their study found that in fatal falls of less than 4 ft, the history was incorrect.

Duhaime et al [5] studied 100 consecutively admitted children with head injuries, age 2 years and younger, to determine injury mechanism and injury types. Findings indicate that most injuries were the result of falls, and that fall heights were found to influence injury types. Most household falls were found to be neurologically benign. Results also revealed that 24% of cases were associated with inflicted trauma and 32% were suspected abuse. This study found that intradural hemorrhages were more likely to be associated with motor vehicle accidents and abusive injury; abuse was the most common cause of mortality. Reece and Sege [47] conducted a retrospective review of 287 children 6.5 years and younger with head injuries to determine the injury mechanism and type of injury. Mechanisms were classified as either definite abuse or accident. Eighteen percent of the cases were classified as accidental, with a mortality rate of 2%, whereas 19% were classified as definite abuse, with mortality rates of 13%. Subarachnoid hemorrhage, SDH, and retinal hemorrhages were more prevalent in the definite abuse cases. Falls were responsible for 58% of the accident cases. In actual falls less than 4 ft, 8% had SDH, 2% had subarachnoid hemorrhages, and none had retinal hemorrhages. In contrast, in abuse cases falsely reported as falls from 4 ft or less, 38% had SDHs, 38% had subarachnoid hemorrhages, and 25% had retinal hemorrhages.

Falls from heights

In one of the earliest examples of injury science, presented in 1942, DeHaven [48] investigated falls from heights of 50 to 150 ft. In the eight cases examined, all subjects survived. DeHaven [48] found that the primary causes of injury were attributable to impact surface and localization of force. Distributing the impact force over time and space can help to ameliorate injury risk. He concluded that "structural provisions to reduce impact and distribute pressure can enhance survival and modify injury"; falls onto yielding surfaces can serve to reduce injury. Richter et al [49] studied vertical deceleration injuries associated with both intentional (suicide) and unintentional high falls, which averaged 7.2 m in height. In 101 subjects, head injuries occurred in 27% of the cases. In this study, severity of injury was correlated with fall height, type of impact surface, and impact position of the body. Striking the ground headfirst corresponded with only a 50% survivability rate. Warner and Demling report that children most frequently tend to impact in the headfirst position in falls [50]. Head injuries are common in pediatric falls [51]. The mortality rate from falls of four stories or less in children (2% to 20%), however, is lower than that in adults (50%). Warner and Demling postulate that the improved survivability in children is likely caused by their lower body mass, which reduces deceleration levels, and their reduced body stiffness because of a greater proportion of cartilage to bone [50, 94]. Lallier et al [52] studied falls in children (mean age 7.4 year) from a height of 10 ft or greater. Major injuries included head trauma in 39% of the cases. Head injuries occurred more frequently in younger children. The authors conclude that the greater surface area of the head relative to the body and higher center of gravity of younger children make them more susceptible to head injury in falls. Overall, head injury was the most frequent reason for hospitalization. Williams [53] prospectively evaluated falls witnessed by a noncaregiver. His study concluded "that infants and children are relatively resistant to injuries from free falls, and falls of less than 10 feet are unlikely to produce serious life-threatening injury."

Short-distance falls are among the most common types of accidents to occur in children. Short falls are also one of the most common falsely reported mechanism of injury in cases of child abuse and inflicted head injury. Plunkett [54] reviewed 18 fall-related head injury fatalities involving equipment, such as swings or platforms. Ages ranged from 12 months to 13 years, with falls ranging from 2 to 10 ft. Distance of fall was defined as the distance of the closest body part rather than center of mass from the ground at the beginning of the fall. If the specific distance could not be determined, a range of possible minimum and maximum height was given. Whether the event was or was not witnessed by a noncaregiver was recorded and in one case, the injury event was videotaped. Plunkett [54] concluded that falls from less than 10 ft may cause fatal head injury, that such injuries may not always be associated with immediate symptoms, and that a history of a short-distance fall in a seriously head-injured patient should not be dismissed. Because of the complexity of each injury event, the recommendation is made that a biomechanical analysis be made for any incident in which the severity of the injury seems to be inconsistent with the history [54].

A 1977 study conducted by Foust et al [55] investigated impact tolerances of the head and lower extremities in free-fall accidents occurring in children, women, and the elderly populations. This study used a combination of techniques and investigative strategies to create an epidemiologic database to analyze injury patterns and define an association between biomechanical measures and injury severity. These researchers relied on scene investigations, medical record assessment, theoretical biodynamic calculations, experimental free falls using anthropometric test devices, and validated two-dimensional computer simulation models to predict key biomechanical impact measures, which have previously been correlated with injury risk. It was found that for given accident conditions, children were generally injured less severely than adults exposed to the same conditions. Simulation models were used to predict whole-body energy, impact velocity, and momentum. Body impact position was also found to have influence on injury risk and resulting injuries. For rigid impact surfaces, researchers showed a relation between types and severity of injury, and age and fall distance. Positive relations between overall abbreviated injury scale and injury severity scale with impact velocity were also found for free falls. Correlations between injury severity level and whole body biomechanical measures were observed only for headfirst-type impact accidents. For children 18 months and younger, a fall distance of 4 to 10 ft was determined to be the threshold for skull fracture. Headfirst falls from greater than 10 ft onto a rigid surface were predicted to result in skull fracture or concussion and at least Abbreviated Injury Scale-2 (AIS-2) injuries for adults and children [55].

Injuries associated with falls from beds

MacGregor [56] evaluated 8343 pediatric emergency department records and determined that 85 were associated with falls from beds. Twenty seven of 85 children sustained a head injury during falls from a bed. Of these 27 cases, there were no skull fractures and no evidence of intracranial bleeding. In a study conducted by Lyons and Oates [57], 207 children who had fallen from either a bed or crib were evaluated to determine type of injury and injury severity. Lyons and Oates [57] sought to answer the question of how likely is it that a fall from a low object, such as a bed, would lead to severe injury. Of the 207 cases, only one head injury (skull fracture) was identified. They concluded that falls from short distances, such as beds and cribs, do not lead to multiple or clinically significant injuries. Additional studies by Nimityongskul and Anderson [58] and Helfer et al [59] evaluating falls from beds support the concept that falls from short distances generally do not result in severe head injuries.

Stairway injuries in children

Joffe and Ludwig [60] sought to describe clinical findings in children 11 years and younger who presented to the emergency department and had fallen down stairs. Injury rarely occurred to more than one body part, and no patient had life-threatening injuries. Chiaviello et al [61] also studied stairway-related injuries. Injuries to more than one body part did not occur. Significant stairway-related injuries were reported in 22% of patients, especially if the fall occurred with the caregiver. Significant injuries included subdurals and skull fractures. There were no deaths. Bertocci et al [62] used computer modeling of a stair fall in a 3 year old and found that the stair number, slope, and surface had an important influence on biomechanical measures associated with injury risk.

Falls will continue to be one of the most common types of injury mechanisms in children and will also be common in false reports of injury in the abused child. Assumptions of what is or is not possible must be replaced with careful and detailed analysis of all of the clinical and social findings, and the biomechanical principles behind both the event and the injuries. If the patient's clinical course is poor, resulting in either a fatal or severally disabled outcome, the history of a minor mechanism is in question [33]. Determining that a mechanism is truly minor, however, requires biomechanical consideration of the injury environment and event. Underlying brain injury is almost always minimal when the mechanism is a low-height fall. This and other studies support the conclusion that significant injuries require greater biomechanical forces and that the type of force determines the particular type of associated injury [5]. The possibility of a serious or even fatal head injury does exist, however, from a short-distance fall and the history of such cannot be assumed to be incorrect [54]. Much work still needs to be done to define injury tolerance better in children and to gain an improved understanding of the types and magnitude of biomechanical forces generated by common childhood injury scenarios and their associated injury potentials. Specifically, the influence of initial conditions, protective reflexes, surface impact, and fall dynamics are integral in evaluating injury potential.

Clinical presentation and course for a given injury and mechanism

Expected behavior and symptoms

When evaluating the stated cause of injury, the history must be analyzed from a biomechanical point of view. Factors to be considered include the following:

1. Is the described behavior of the child during and after the trauma event consistent with the clinical findings?
2. What are the developmental capabilities of the child?
3. Did the child loose consciousness?
4. Was there a lucid interval?
5. Are there other injuries that negate the possibility of the child behaving normally after the injury, such as a transverse fracture of the femur, or liver laceration?
6. Was there evidence of a hypoxic-ischemic event or a delay in seeking care?
7. Were the clinical symptoms of serious injury subtle or even occult, and the delay because of lack of recognition of a problem?
8. Do the facts of the story as told by the caregiver remain consistent, or does the story change to try and retrofit any newly discovered injuries?

It is critical that medical personnel not jump to conclusions and that additional information is gathered as needed to make sense of or refute the history and injuries from a biomechanical perspective, and to ensure safety for the child and family.

Other contributing factors

Multiple primary trauma events must be considered as a possibility in the infant presenting with a severe head injury. Further complicating the evaluation is the common occurrence of repeat primary traumatic events over days, weeks, or even months. Repetitive slapping, throwing, or shaking the infant may result in multiple, subclinical concussive events. This adds to the complexity of determining what happened and when it occurred. Is one seeing the results of a single event, or the results of multiple, repetitive insults?

Experimental head injury models

Many combinations of forces and accelerations can result from a traumatic event that may lead to brain injury. Accordingly, there have been many studies in support of developing brain injury criteria, most of which are based on the input forces or accelerations delivered to the head. Various, sometimes conflicting, theories have been postulated to predict the type of head injury that may result from given forces or accelerations imparted to the head. Most of the studies can be classified based on either head impact or head acceleration models. Acceleration models can be grouped further by either rotational or translational accelerations of the head.

Direct-impact head injury models

Direct-impact head injury studies can be grouped into those that permit free movement of the head following impact and those that constrain head movement on impact. Early experiments conducted by Gurdjian et al [63] in anesthetized primates used a piston impactor to investigate impact force, head accelerations, and resulting injuries in primates. In these experiments, the neck was used as the only means of constraint, allowing for a complex dynamic response of the head making it difficult to determine a cause and effect relationship. Injury severity, however, was found to be a function of impact velocity, impactor material properties, impactor mass, and impactor contact area [11]. Subsequent studies attempted to constrain head motion to a single plane during and following impact so that reproducibility in injury could be attained [64–66].

Additional direct-impact studies were also conducted in cats and dogs using a captive bolt head impactor to study cerebral contusion and edema [36,67–69]. Efforts have also been made to study direct head impact in rats; success has been limited, however, because convulsion is a common response in rats and may affect interpretation of resulting injuries [8,70,71]. In 1991, Goldman et al [72] used a pendulum impact model to investigate mild head injury in rats associated with direct impact. In these studies, Goldman et al [72] attempted to prevent skull fracture by resting the skull on an energy-absorbing pad. A key outcome of these experiments was a description of the relationships between severity of injury, body mass, skull strength, and impact loading parameters in the rat.

Acceleration-based head injury models

Early studies by Holburn [73] using photoelastic models determined that rotational accelerations could produce concussive head injury. Gurdjian et al [74] postulated that head rotation, which leads to brain movement relative to the skull, could lead to injury. Ommaya et al [75] conducted studies in primates to describe the effects of head acceleration in 1966. These studies found that whiplash-type motion, resulting from indirect head forces, could lead to concussion. Ommaya et al [75] also studied direct impact and rotation of the head, demonstrating that concussion could also result from such mechanical input. Through this work it was determined that direct rotational acceleration levels, which were half that necessary to produce indirect rotational loading concussions, could produce concussions.

Ommaya and Genneralli [76] conducted subsequent experimental studies comparing the effects of rotational and translational accelerations. These experiments showed that diffuse injuries resulted only from rotational acceleration. Loss of consciousness was also more readily produced in this series of experiments at high levels of rotational acceleration than at high levels of translational acceleration [76,77]. In a subsequent series of controlled experiments, Abel et al [78] investigated the relationship between tangential acceleration in the sagittal plane and the presence of SDHs. A tangential acceleration of 714 g was defined as the threshold for SDHs. Genneralli et al [35] isolated and studied the effects of rotational deceleration in 1982. Their experiments expanded on previous studies through the additional factor of time exposure to deceleration. In general, their findings predicted that concussion and diffuse brain injury could result from decreasing levels of deceleration when time exposure was increased. Both the levels of deceleration and the duration of exposure to this deceleration are keys to predicting injury risk. Experiments have shown that two factors, acceleration and the time over which the acceleration occurs (time exposure), influence head injury risk and severity. Large rotational accelerations occurring over short periods of time typically result in SDH, whereas longer exposures to acceleration are often associated with DAI [7]. Lee et al [79] and Lee and Haut [80] conducted experiments that describing the relationships between tangential and rotational accelerations and the threshold for SDH in rhesus monkeys. In 1982, Gennarelli et al [35] studied the biomechanics of SDHs by investigating the effects of coronal plane head acceleration. Margulies et al [81] visualized the effects of coronal acceleration by using simulated silicone gel human and baboon brain models. These models allowed for estimation of critical shear strain and a threshold coronal plane rotational acceleration for DAI in humans.

Repetitive head acceleration generated through indirect forces is also of interest, especially as it relates to the concept of "shaken baby syndrome." In a cat animal model, Nelson et al [82] and Barron et al [83] found that repetitive nonimpact accelerations were capable of producing immediate death, extended coma, or delayed mortality.

Injury criteria

Over the past 40 years, a great deal of effort has been devoted to the investigation of head injury mechanisms and the development of injury criteria. The most widely used criteria, to date, is the Head Injury Criteria (HIC), which was proposed in 1972 by the National Highway Transportation Safety Administration (NHTSA). The HIC have been developed to assess head injury risk associated with direct-impact events. The origins of the HIC are based on experiments conducted by Lissner et al [84] in 1960. In these experiments, embalmed cadaver heads were impacted on rigid surfaces to determine the accelerations which were associated with the onset of skull fractures. Because concussions were found to be present in 80% of skull fractures, test results could infer the onset of concussion. This work was compiled to represent the Wayne State Tolerance Curve (WSTC), which characterizes the relationship between acceleration, acceleration duration, and onset of concussion-fracture. The WSTC was later modified to include a wider range of acceleration exposures and to include findings associated with animal and human volunteer experiments [85]. Gadd [86] further enhanced the WSTC by adding data from long duration exposures and other primate sled tests, which resulted in the Gadd Severity Index. In 1971, Versace [50] proposed the HIC, which was subsequently slightly modified to include long duration human subject testing and was adopted by NHTSA in 1972. The HIC is based on a time weighting of the resultant translation head acceleration. The Federal Motor Vehicle Safety Standards limits the HIC value to 1000 for a mid-sized male test dummy.

Recently, NHTSA attempted to adapt the HIC established for mid-sized men to various sized crash victims. To do so, scaling factors must account for both geometric and material property differences. Material properties specific to the cranial sutures were chosen as the key scaling property reflecting resistance to skull fracture in children. Accounting for these factors, the NHTSA Notice of Proposed Rulemaking proposed HIC values for children (Table 1). The probability of skull fracture ($AIS \geq 2$) associated with the proposed NHTSA HIC limits is estimated to be 47% across all test dummies [87,88].

Despite its wide usage, the HIC have important limitations. One limitation is the fact that the HIC are based solely on translational acceleration associated with impact. In most head injury events, it is common to have combined loading, which consists of both rotational and translational accelerations. To account for such combined loading, a model accounting for the complex mechanical response of brain tissue is required.

Other efforts related to the development of head injury tolerance levels include the work by Ommaya et al [89,90] to determine threshold levels of nonimpact angular acceleration and velocity. Nonimpact angular acceleration has been associated with DAI ranging from concussion to coma. Ommaya's experiments were based on primate testing, which were then scaled to establish an injury threshold for adult humans. The threshold reflected the relationship between angular acceleration, angular velocity, duration of exposure, and presence of concussion. Ommaya's head angular injury criteria were then further scaled to children using head mass and length scaling factors [91].

As shown in Table 2 , children are able to tolerate a higher level of angular acceleration and velocity before onset of DAI. Working with Ommaya's et al data, Sturtz [92] formulated angular acceleration injury criteria for 6 and 3 year olds based on both impact and nonimpact events. Sturtz criteria also differentiated between duration exposures (Table 3). As shown in Table 3, as the duration of acceleration exposure increases the tolerance to acceleration decreases. Additionally, younger children are able to tolerate a higher level of acceleration before onset of DAI.

Margulies and Thibault [93] also conducted primate studies and developed physical and analytic models to establish injury thresholds associated

Table 1
HIC values for children

Test dummy	Mid-sized male	6 year old	3 year old	1 year old
Proposed HIC Limit	1000	1000	900	660

Table 2
Ommaya's head angular acceleration scaled injury criteria

	Angular velocity limit (rad/sec)	Angular acceleration limit (rad/sec^2)
Adult	30	<1700
6 year old	33	<2106
3 year old	34	<2255
1 year old	37	<2524

with angular acceleration and velocity. Using a mass scaling factor, they also described the relationship between angular acceleration, angular velocity, and the onset of DAI for infants.

Summary

Much of what is understood as potential for injury is based in what has been observed clinically. This knowledge base is critical for decision making but has inherent and important limitations. Experimental studies investigating the influence of environmental factors, such as height of fall and surface type on injury potential, add important information, but also have inherent limitations. Important trends and predictions of probable injury can be studied but inference to a specific child's injuries is difficult because of unaccounted for contributing factors of injury risk. Such factors include muscle contraction, protective reflexes, and specific tissue response to trauma forces. Additional biomechanical research is needed to bridge the gap between clinical observations and experimental predictions.

The specific and unique perspective of the neurosurgeon is a critical piece in differentiating accidental and nonaccidental head injury with experience and reason as the basis of the conclusion. Do the physics of the injury match the mechanistic principals of the described injury event? Could all of the injuries result from the event? Is it plausible that these set of injuries occurred from the described event based on the physician's experience and the current scientific understanding of injury biomechanics? Do the mechanical forces of the reported mechanism and injuries match?

Table 3
Sturtz scaled angular acceleration tolerances (rad/sec^2)

Duration	Impact type	Adult	6 year old	3 year old
10 ms	Indirect	7020	7390	8140
3 ms	Indirect	70,200	73,900	81,400
10 ms	Direct	71,732	1823	2008
3 ms	Direct	7900	8300	9100

To determine that an explanation is plausible requires consideration of all the facts and injuries, consideration of the described behavior, and consistency with the neurologic status. These facts of the case are compared with medical knowledge and the learned experience of the neurosurgeon. The answer to the question ''is it possible?'' is based on clinical experience and objective reasoning. Rather than a black box question and answer based in unrealistic probability, the answer is based on the facts of the case and physical principles that govern biomechanics and resultant injuries.

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