Head Injury Depth as an Indicator of Causes and Mechanisms

WHAT'S KNOWN ON THIS SUBJECT: Young victims of abusive head trauma frequently manifest acute cardiorespiratory compromise, diffuse brain swelling, and poor outcomes. Deep, focal, hemorrhagic and axonal injuries were observed near the craniocervical junction in infants who died as a result of abuse.

WHAT THIS STUDY ADDS: For infants and young children, head injury depth is a useful indicator of head injury causes and mechanisms. These results have diagnostic, prognostic, and forensic significance.

abstract

FREE

OBJECTIVE: The goal was to measure differences in the causes, mechanisms, acute clinical presentations, injuries, and outcomes of children <36 months of age with varying "greatest depths" of acute cranial injury.

METHODS: Children <36 months of age who were hospitalized with acute head trauma were recruited at multiple sites. Clinical and imaging data were collected, and caregivers underwent scripted interviews. Neurodevelopmental evaluations were completed 6 months after injury. Head trauma causes were categorized independently, and subject groups with varying greatest depths of injury were compared.

RESULTS: Fifty-four subjects were enrolled at 9 sites. Twenty-seven subjects underwent follow-up neurodevelopmental assessments 6 months after injury. Greatest depth of visible injury was categorized as scalp, skull, or epidural for 20 subjects, subarachnoid or subdural for 13, cortical for 10, and subcortical for 11. Compared with subjects with more-superficial injuries, subjects with subcortical injuries more frequently had been abused (odds ratio [OR]: 35.6; $P < .001$), more frequently demonstrated inertial injuries ($P < .001$), more frequently manifested acute respiratory (OR: 43.9; $P < .001$) and/or circulatory (OR: 60.0; $P < .001$) compromise, acute encephalopathy (OR: 28.5; $P = .003$), prolonged impairments of consciousness (OR: 8.4; $P = .002$), interhemispheric subdural hemorrhage (OR: 10.1; $P = .019$), and bilateral brain hypoxia, ischemia, or swelling (OR: 241.6; $P < .001$), and had lower Mental Developmental Index ($P = .006$) and Gross Motor Quotient ($P < .001$) scores 6 months after injury.

CONCLUSION: For children <3 years of age, head injury depth is a useful indicator of injury causes and mechanisms. *Pediatrics* 2010;125:712–720

AUTHORS: Kent P. Hymel, MD,[a] Michael A. Stoiko, MD,[b] Bruce E. Herman, MD,[c] Amy Combs, LMSW,[d] Nancy S. Harper, MD,[e] Deborah Lowen, MD,[f,g] Katherine P. Deye, MD,[h,i] Karen Homa, PhD,[j] and James A. Blackman, MD, MPH[k,l]

[a]Department of Pediatrics, Dartmouth Medical School, Children's Hospital at Dartmouth-Hitchcock Medical Center, Lebanon, New Hampshire; [b]Department of Pediatrics, Michigan State University School of Medicine, Spectrum Health Hospitals and Helen DeVos Children's Hospital, Grand Rapids, Michigan; [c]Department of Pediatrics, University of Utah School of Medicine, Primary Children's Medical Center, Salt Lake City, Utah; [d]Center for Child Protection, Spectrum Health Hospitals and Helen DeVos Children's Hospital, Grand Rapids, Michigan; [e]Department of Pediatrics, Texas A&M University, Driscoll Children's Hospital, Corpus Christi, Texas; [f]Department of Pediatrics, University of Oklahoma College of Medicine, Tulsa, Oklahoma; [g]Children's Justice Center, Tulsa, Oklahoma; [h]Department of Pediatrics, Inova Fairfax Hospital for Children, Falls Church, Virginia; [i]Department of Pediatrics, National Children's Medical Center, Washington, DC; [j]Leadership Preventive Medicine Residency Program, Dartmouth-Hitchcock Medical Center, Lebanon, New Hampshire; [k]Department of Pediatrics, University of Virginia Children's Hospital, Charlottesville, Virginia; and [l]Department of Pediatrics, Kluge Children's Rehabilitation Center, Charlottesville, Virginia

KEY WORDS

depth of injury, head trauma, infants, abuse, accidents

ABBREVIATIONS

CI—confidence interval
CT—computed tomography
GMQ—Gross Motor Quotient
MDI—Mental Developmental Index
MVC—motor vehicle crash
OR—odds ratio
PediBIRN—Pediatric Brain Injury Research Network
SDH—subdural hematoma

www.pediatrics.org/cgi/doi/10.1542/peds.2009-2133

doi:10.1542/peds.2009-2133

Accepted for publication Nov 25, 2009

Address correspondence to Kent P. Hymel, MD, Dartmouth-Hitchcock Medical Center, Department of Pediatrics, One Medical Center Dr, Lebanon, NH 03756-0001. E-mail: kphymel@gmail.com

PEDIATRICS (ISSN Numbers: Print, 0031-4005; Online, 1098-4275).

FINANCIAL DISCLOSURE: *The authors have indicated they have no financial relationships relevant to this article to disclose.*

Funded by the National Institutes of Health (NIH).

In young children, the traumatic cranial injuries that result from accidental, short-distance falls tend to be superficial. Acute encephalopathy, acute respiratory or circulatory compromise, diffuse brain hypoxia-ischemia or swelling, and poor outcomes are rare in such cases.[1–17]

In contrast, the traumatic cranial injuries that result from child abuse tend to be deeper and/or more diffuse.[5,7,18–21] Neuropathological studies of abused infants revealed hemorrhagic and axonal injuries in the base of the brain and in the upper spinal cord, which seem to trigger acute respiratory and/or circulatory compromise.[22–24] If not promptly recognized or treated, such compromise may initiate and/or exacerbate the development of secondary, diffuse, hypoxic-ischemic brain injuries, which have been linked to poor outcomes.[5,7,18–21]

Our research objective was to conduct a prospective, multicenter, cohort study that would measure differences in head injury causes, mechanisms, acute clinical presentations, and neurodevelopmental outcomes among infants and young children with acute traumatic injuries of varying "greatest depth" visible on neuroimaging scans. We hypothesized that deep, traumatic, cranial injuries in infants and young children could be linked to abusive causes and inertial injury mechanisms that increase the risk or incidence of acute respiratory or circulatory compromise, bilateral brain hypoxia-ischemia or swelling, and abnormal neurodevelopmental outcomes.

METHODS

Pediatric Brain Injury Research Network

The Pediatric Brain Injury Research Network (PediBIRN) is a consortium of clinical investigators who made a voluntary commitment to conduct collaborative, multicenter, clinical research regarding traumatic brain injuries in infants and young children. The institutional review boards at all 9 participating PediBIRN institutions approved this research study before local subject recruitment was initiated.

Participants

At every participating PediBIRN site, investigators compared hospital admission and computed tomography (CT) logs and then screened specific medical records to identify eligible subjects. Inclusion criteria included age of $<$36 months and CT evidence of any acute, nonpenetrating, head or brain injury leading to inpatient evaluation or treatment. Exclusion criteria included preexisting central nervous system or brain disease, infection, hypoxia-ischemia, or trauma, birth injury, developmental delays, sensory deficits, bleeding disorders, and severe malnutrition. Screening for study exclusion criteria was completed after study enrollment, through detailed, fully scripted, parent interviews, plotting and interpretation of growth parameters, and subsequent blinded reviews of the subjects' initial cranial CT scans.

Procedures

Subjects were examined serially during the course of their acute hospitalizations. Local researchers reviewed their emergency medical services, emergency department, and inpatient medical records to capture extensive demographic, historical, clinical, laboratory, and neurosurgical data. Primary caregivers (ie, the persons responsible for the children when they were injured or became clearly and persistently ill with clinical signs later linked to their acute, traumatic, cranial injuries) were interviewed in fully scripted interviews designed to capture extensive historical and clinical data from the scene of injury, in a consistent manner. More specifically, every primary caregiver who consented to be interviewed was questioned systematically regarding the specific timing, cause (abusive versus nonabusive), and circumstances of the injury; the child's clinical and mental status before and after acute clinical deterioration; and medical interventions at the scene of the injury. Qualified neuroradiologists who were blinded with respect to all historical and clinical information reviewed the subjects' complete cranial CT and MRI studies, to document injuries and to identify the greatest depth of visible primary or secondary injury.

Follow-up Neurodevelopmental Assessments

The surviving subjects were invited to return 6 months after injury for an extensive, outpatient, neurodevelopmental assessment that included the Bayley Scales of Infant Development II. The fully qualified physical or occupational therapists, rehabilitation specialists, or developmental pediatricians who conducted the assessments at each participating site were blinded with respect to all historical, clinical, and radiologic information. The Mental Developmental Index (MDI) and Gross Motor Quotient (GMQ) scores calculated during these follow-up assessments were used as outcome measures of overall cognitive and motor development, respectively. Both scores are standardized scores like IQ scores, with SDs of 15 and mean values of 100.

Statistical Analyses

All data were recorded on data forms that had been pilot-tested extensively at 2 PediBIRN institutions. Subsequently, the data were transferred into a relational database (Access 2000 [Microsoft, Redmond, WA]). Cases were sorted into comparison groups reflecting the depths, causes, and mechanisms of the observed head injuries.

To sort cases according to cause of injury, we applied definitional criteria specifically designed to reflect an emerging consensus, to be free of any references to specific injuries or injury severity, and to minimize circular reasoning and inherent biases (Table 1). To sort cases according to required mechanisms of injury, every subject's specific cranial injuries were listed and then classified (Table 2). Injuries resulting solely from tissue distortions induced by cranial impact and/or skull deformation were classified as contact injuries. Injuries resulting solely from tissue distortions induced by rotational cranial acceleration or deceleration were classified as inertial injuries. Cases then were categorized as revealing (1) isolated contact injuries, (2) isolated inertial injuries, (3) combined (ie, contact and inertial) injuries, or (4) isolated undetermined (ie, contract or inertial) injuries.

Fisher's exact test was used to compare the frequencies of categorical variables among the 4 comparison groups defined according to the greatest depth of visible injury, categorized as scalp, skull, or epidural; subarachnoid or subdural; cortical brain; or subcortical brain. For continuous measures, the Kruskal-Wallis test was used to assess equality of the comparison groups. The Wilcoxon rank-sum test was used to compare subjects with subcortical greatest depth of visible injury with the other comparison groups, with more-superficial injuries. Finally, univariate logistic regression was used to calculate odds ratios (ORs) for specific findings linked to subcortical greatest depth of injury visible on neuroimaging scans.

RESULTS

Twenty-seven eligible subjects were recruited at the University of Virginia (Charlottesville, VA) or Inova Fairfax Hospital for Children (Falls Church, VA) dur-

TABLE 1 Criteria for Categorizing Causes of Head Injuries

Category	Criteria
Abusive	Cases in which primary caregiver admitted abusive acts that resulted in acute clinical signs linked to child's acute traumatic cranial injuries
	Cases in which primary caregiver's abusive acts were witnessed independently and resulted in acute clinical signs linked to child's acute traumatic cranial injuries
	Cases in which child not yet cruising or walking first manifested acute clinical signs linked to acute traumatic cranial injuries while in the care of primary caregiver who specifically denied that child had experienced any trauma
	Cases in which primary caregiver provided explanation for child's acute clinical signs and acute traumatic cranial injuries that was clearly developmentally inconsistent with parents' description of child's developmental capabilities
	Cases in which primary caregiver provided explanation for child's acute clinical signs and acute traumatic cranial injuries that was clearly historically inconsistent with repetition over time
	Cases in which child with acute head injury demonstrated ≥2 categories of noncranial injuries considered moderately or highly specific for abuse
Nonabusive	Cases in which primary caregiver described accidental head injury event that was developmentally consistent with parents' description of child's developmental capabilities, was historically consistent with repetition over time, could be linked to child's acute clinical presentation for acute traumatic cranial injuries, and occurred in the absence of noncranial injuries considered moderately or highly specific for abuse
	Cases in which accidental head injury event (eg, MVC) was witnessed independently and could be linked to child's acute clinical presentation with acute traumatic cranial injuries
Undetermined	Cases meeting criteria for both abusive and nonabusive causes
	Cases not meeting any criteria for either abusive or nonabusive causes
	Cases in which primary caregiver could not be interviewed

The primary caregiver was defined as the person responsible for the child when the child first became clearly and persistently ill with clinical signs later linked to his or her acute traumatic cranial injuries. Noncranial injuries considered moderately or highly specific for abuse included classic metaphyseal lesions; fractures of the ribs, scapula, sternum, spinous processes, or digits; vertebral body fractures or dislocations; epiphyseal separations; noncranial bruising, abrasions, or lacerations in locations other than the knees, shins, or elbows; patterned bruises or dry-contact burns; scalding burns with uniform depth, clear lines of demarcation, and a paucity of splash marks; intraabdominal injuries; retinal hemorrhage described by an ophthalmologist as dense, extensive, covering a large surface area of the retina, or extending to the periphery of the retina; and retinoschesis diagnosed by an ophthalmologist.

TABLE 2 Injury Classification Reflecting Required Mechanisms of Injury

Category	Injuries
Primary cranial injuries that require contact mechanisms of injury	Craniofacial soft-tissue injuries, subgaleal hematomas, cephalohematomas, skull fractures, epidural hematomas
Primary cranial injuries that require inertial mechanisms of injury	Acute encephalopathy, diffuse axonal injuries
Primary cranial injuries resulting from undetermined (ie, either contact or inertial) mechanisms of injury	Subarachnoid hemorrhage, brain contusions, brain lacerations, any abnormal subdural collections

Primary traumatic cranial injuries begin at the moment of injury and result from the tissue distortions induced through contact and/or inertial injury mechanisms. Contact injuries are primary injuries that result solely from cerebral tissue distortions induced by cranial impact and/or skull deformation. Contact injuries can be viewed as primary injuries that result from cranial impact if the head is fixed and prevented from moving. Inertial injuries are primary injuries that result solely from the cerebral tissue distortions induced by cranial acceleration or deceleration, irrespective of whether there was direct impact to the cranium. Acute encephalopathy was defined as primary caregiver verification or emergency medical services/emergency department documentation of complete loss of consciousness at the scene of injury or primary caregiver verification or emergency medical services/emergency department documentation of both alteration of consciousness and difficulty arousing from sleep before hospital admission.

ing a 2.5-year period between 2003 and 2006. The remaining PediBIRN sites enrolled a convenience sample of 27 additional subjects during the same time period. Overall, 54 study subjects who met eligibility criteria were enrolled.

The greatest depth of cranial injury visible on neuroimaging scans was categorized as scalp, skull, or epidural for 20 subjects, subarachnoid or subdural for 13, cortical brain for 10, and subcortical brain for 11. Among the subjects who met the definitional criteria for nonabusive head trauma were 4 children who sustained head injuries in motor vehicle crashes (MVCs) and 26 whose injuries were attributed to falls. The falls included 4 involving stairs, 3 from heights of >10 feet, and 2 from heights of 6 to 10 feet. The remaining subjects ($n = 17$) reportedly fell from heights of <6 feet.

Demographic, etiologic, mechanistic, clinical, neuroimaging, and outcome data for the 4 comparison groups are summarized in Table 3. Fisher's exact test revealed statistically significant differences in age and ethnicity, but not gender or race, between comparison groups. Subjects with the most-superficial injuries tended to be older than subjects with deeper injuries.

Additional analyses revealed significant differences in head injury causes, mechanisms, acute clinical presentations, and outcomes among the 4 comparison groups. These differences were almost exclusively among subjects with subcortical injuries. Compared with all subjects with more-superficial injuries, subjects with subcortical greatest depth of visible injury (1) more frequently met definitional criteria for abuse (OR: 35.6 [95% confidence interval [CI]: 6.0–209.0]; $P < .001$; sensitivity: 0.73; specificity: 0.93); (2) more frequently manifested injuries requiring an inertial mechanism (sensitivity: 1.00; specificity: 0.72; Fisher's exact test, $P < .001$); (3) had lower initial Glasgow Coma Scale scores (OR: 0.59 [95% CI: 0.36–0.74]; $P < .001$); (4) more frequently manifested acute respiratory compromise (OR: 43.9 [95% CI: 6.9–277.8]; $P < .001$; sensitivity: 0.82; specificity: 0.91), acute circulatory compromise (OR: 60.0 [95% CI: 8.7–413.3]; $P < .001$; sensitivity: 0.82; specificity: 0.88), acute encephalopathy (OR: 28.5 [95% CI: 3.0–224.2]; $P = .003$; sensitivity: 1.00; specificity: 0.67), and prolonged impairments of consciousness (OR: 8.4 [95% CI: 2.2–31.5]; $P = .002$; sensitivity: 0.73; specificity: 1.00); (5) more frequently demonstrated interhemispheric subdural bleeding (OR: 10.1 [95% CI: 1.5–69.9]; $P = .019$; sensitivity: 0.82; specificity: 0.91) and bilateral brain hypoxia, ischemia, or swelling (OR: 241.6 [95% CI: 15.4–2315.9]; $P < .001$; sensitivity: 0.64; specificity: 0.91); and (6) had lower MDI (Wilcoxon test, $P = .006$) and GMQ (Wilcoxon test, $P < .001$) standardized scores 6 months after injury. Both subjects who died had subcortical injuries.

Eight (73%) of 11 "abused" subjects demonstrated subcortical greatest depth of visible injury on neuroimaging scans. In contrast, only 2 (7%) of 30 "nonabused" subjects, both of whom were improperly restrained victims of a MVC, demonstrated subcortical greatest depth of injury. With exclusion of the 4 subjects who sustained head injuries in MVCs, all subjects with isolated scalp, skull, or epidural injuries ($n = 13$) experienced a head injury event categorized independently as nonabusive. The largest proportion (38%) of cases with undetermined causes of injury involved subjects with subarachnoid or subdural greatest depth of visible injury (Fig 1).

Contact injuries were confirmed for 9 (69%) of 13 subjects with subarachnoid or subdural greatest depth of visible injury and for 8 (80%) of 10 subjects with cortical greatest depth of visible injury. In contrast, 11 (100%) of 11 subjects with visible subcortical injuries manifested inertial injuries, 7 (64%) of 11 manifested inertial injuries in isolation, and none manifested isolated contact injuries (Fig 2).

Crying and/or irritability before hospital admission was documented for 7 (64%) of 11 subjects who later demonstrated subcortical injuries, including 6 (55%) of 11 who also experienced acute encephalopathy before hospital admission. All 11 subjects who eventually demonstrated subcortical injuries on neuroimaging scans experienced at least brief impairment or loss of consciousness at the scene of the injury, and 8 (73%) experienced impairment or loss of consciousness that persisted for >24 hours. None of the subjects with more-superficial greatest depth of visible injury experienced such prolonged impairment or loss of consciousness. In contrast, 15 (75%) of 20 subjects with scalp, skull, or epidural greatest depth of visible injury experienced no impairment or loss of consciousness, as did 8 (62%) of 13 subjects with subarachnoid or subdural greatest depth of visible injury and 8 (80%) of 10 subjects with cortical greatest depth of visible injury (Figs 3 and 4).

Respiratory compromise before hospital admission was observed or reported for 9 (82%) of 11 subjects with subcortical greatest depth of visible injury but only 4 (9%) of 43 subjects with more-superficial greatest depth of visible injury. Similarly, circulatory compromise was documented for 9 (82%) of 11 subjects with subcortical injuries but only 5 (12%) of 43 subjects with more-superficial greatest depth of injury (Fig 3).

Among 43 subjects with scalp, skull, or epidural, subarachnoid or subdural, or cortical brain greatest depth of visible injury, craniofacial soft-tissue injuries were identified for 33 (77%) and

TABLE 3 Demographic, Etiologic, Mechanistic, Clinical, Neuroimaging, and Outcome Data for Subject Comparison Groups

	Scalp, Skull, or Epidural ($N = 20$)[a]	Subarachnoid or Subdural ($N = 13$)[a]	Cortical Brain ($N = 10$)[a]	Subcortical Brain ($N = 11$)[a]	P[b]
Age at time of injury, mo					.049
Median	15.5	3	3	5	
Mean	14.5	5	8	8.5	
SD (range)	10.5 (0.5–31)	7 (0.5–27)	10.5 (0.5–28)	8.5 (0.5–26)	
Gender, *n* (%)					.786
Female	10 (50)	6 (46)	6 (60)	4 (36)	
Male	10 (50)	7 (54)	4 (40)	7 (64)	
Race, *n* (%)					.160
White	14 (70)	12 (92)	9 (90)	8 (73)	
Black	3 (15)	1 (8)	0 (0)	0 (0)	
Other	3 (15)	0 (0)	1 (10)	3 (27)	
Ethnicity, *n* (%)					.003
Hispanic	0 (0)	0 (0)	1 (10)	4 (36)	
Non-Hispanic or unknown	20 (100)	13 (100)	9 (90)	7 (64)	
Cause of injury, *n* (%)[c]					<.001
Abusive	0 (0)	1 (8)	2 (20)	8 (73)	
Nonabusive	15 (75)	7 (54)	6 (60)	2 (18)	
Undetermined	5 (25)	5 (38)	2 (20)	1 (9)	
Inferred mechanisms of injury, *n* (%)[d]					<.001
Isolated contact	15 (75)	5 (38)	6 (60)	0 (0)	
Isolated inertial	0 (0)	1 (8)	0 (0)	7 (64)	
Combined	5 (25)	4 (31)	2 (20)	4 (36)	
Undetermined	0 (0)	3 (23)	2 (20)	0 (0)	
Acute clinical presentation, *n* (%)					
Crying/irritability before admission	12 (60)	9 (69)	7 (70)	7 (64)	.843
Vomiting before admission	5 (25)	7 (54)	4 (40)	4 (36)	.378
Respiratory compromise before admission[e]	2 (10)	0 (0)	2 (20)	9 (82)	<.001
Circulatory compromise before admission[f]	1 (5)	2 (15)	2 (20)	9 (82)	<.001
Severe pallor or cyanosis before admission	2 (10)	2 (15)	1 (10)	5 (45)	.027
Seizures before admission	1 (5)	1 (8)	1 (10)	5 (50)	.014
Acute encephalopathy before admission[g]	5 (25)	5 (38)	4 (40)	11 (100)	<.001
Delayed impairment of consciousness	1 (5)	0 (0)	1 (10)	3 (27)	.121
Decorticate or decerebrate posturing	0 (0)	0 (0)	0 (0)	4 (36)	.002
Duration of impaired consciousness, *n* (%)					<.001
None reported or documented	15 (75)	8 (62)	8 (80)	0 (0)	
Only at scene of injury	4 (20)	5 (38)	1 (10)	3 (27)	
Upon admission; responsive by 24 h	1 (5)	0 (0)	1 (10)	0 (0)	
>24 h, without deterioration[h]	0 (0)	0 (0)	0 (0)	2 (18)	
>24 h, with deterioration[h]	0 (0)	0 (0)	0 (0)	6 (55)	
Initial Glasgow Coma Scale score					<.001[i]
n	19	13	10	11	
Mean	13.7	14.2	13.5	6.4	
SD (range)	2.3 (6–15)	1.1 (12–15)	1.4 (11–15)	3.7 (3–15)	
Pediatric Trauma Scale score					.001[i]
n	17	11	9	10	
Mean	8.8	8.5	8.4	5.0	
SD (range)	1.6 (4–11)	1.1 (7–11)	0.9 (7–10)	2.5 (1–10)	
Injuries visible through neuroimaging, *n* (%)					
Any craniofacial soft-tissue injuries	18 (90)	7 (54)	8 (80)	4 (36)	.008
Any skull fractures	19 (95)	6 (46)	6 (60)	2 (18)	<.001
Isolated, nondiastatic, linear, parietal	10 (50)	4 (31)	2 (20)	0 (0)	.021
Any "high-energy" skull fractures[j]	2 (10)	1 (8)	2 (20)	1 (9)	.111
Epidural hematoma	3 (15)	0 (0)	1 (10)	0 (0)	.360
Any abnormal subdural collection	NA	9 (69)	4 (40)	11 (100)	.009
Interhemispheric	NA	4 (31)	0 (0)	9 (82)	<.001
Bilateral	NA	3 (23)	1 (10)	7 (64)	.033
Unilateral	NA	5 (38)	3 (30)	2 (18)	.576
Small focal	NA	2 (15)	3 (30)	0 (0)	.191
Any subarachnoid hemorrhage	NA	9 (69)	2 (20)	3 (27)	.028
Any brain contusions	NA	NA	8 (80)	7 (64)	.635

TABLE 3 Continued

	Scalp, Skull, or Epidural ($N = 20$)[a]	Subarachnoid or Subdural ($N = 13$)[a]	Cortical Brain ($N = 10$)[a]	Subcortical Brain ($N = 11$)[a]	P[b]
Any brain hypoxia-ischemia or swelling	NA	NA	3 (30)	11 (100)	.001
Unilateral	NA	NA	2 (20)	2 (18)	1.00
Bilateral	NA	NA	1 (10)	9 (82)	.002
Brain shifting or herniation (>3 mm)	1 (5)	1 (8)	0 (0)	4 (36)	.037
Outcomes					
Length of hospital stay, d					.001[i]
n	19	11	9	8	
Mean	2.3	4.7	6	24	
SD (range)	1.2 (1–5)	2.9 (2–10)	7.7 (1–25)	13.8 (11–52)	
Death resulting from acute cranial injuries, *n* (%)	0 (0)	0 (0)	0 (0)	2 (18)	.070
MDI standardized score 6 mo after injury					.004[i]
n	10	6	7	3	
Mean	94	110	93	50	
SD (range)	9.7 (73–105)	9.9 (98–120)	13 (70–112)	0 (50–50)	
GMQ standardized score 6 mo after injury					.005[i]
n	7	4	7	5	
Mean	97	106	103	51	
SD (range)	9.5 (85–111)	6.7 (96–111)	9.4 (89–115)	17.9 (38–83)	

NA indicates not applicable.

[a] Greatest depth of primary or secondary cranial injury visible through neuroimaging.

[b] As measured with Fisher's exact test (for nominal variables) or Kruskal-Wallis test (for continuous variables).

[c] See Table 1 for a priori definitional criteria used to categorize each subject's cause of injury.

[d] See Table 2 for injury classification scheme used to categorize each subject's inferred mechanisms of injury. Among subjects with visible contact injuries, cranial acceleration or deceleration could not be excluded with certainty. However, visible and/or verifiable inertial injuries were not identified. Among subjects with visible or verifiable inertial injuries, cranial impact could not be excluded with certainty. However, visible contact injuries were not identified.

[e] Respiratory compromise was defined as labored or infrequent respirations, apnea, or any requirement for mouth-to-mouth breathing, bag-mask ventilation, or intubation occurring at the scene of injury, during transport, in the emergency department, or at the time of hospital admission and specifically documented by medical personnel or reported by the child's primary caregiver.

[f] Circulatory compromise was defined as bradycardia (ie, >35 beats per minute below normal mean heart rate for age), delayed capillary refill, absent or weak pulses, narrow pulse pressure, hypotension, or any requirement for chest compressions, rapid volume expansion, or epinephrine therapy occurring at the scene of injury, during transport, in the emergency department, or at the time of hospital admission and specifically documented by medical personnel or reported by the child's primary caregiver.

[g] Acute encephalopathy was defined as complete loss of consciousness or combined difficulty arousing from sleep and alteration of consciousness occurring at the scene of injury, during transport, in the emergency department, or at the time of hospital admission and specifically documented by medical personnel or reported by the child's primary caregiver.

[h] Deterioration included decorticate posturing, decerebrate posturing, and flaccidity.

[i] Statistical differences among the 4 subject comparison groups and posthoc comparisons of the subcortical group with the other 3 (combined) groups with more-superficial injuries revealed significant differences in Glasgow Coma Scale scores, Pediatric Trauma Scale scores, length of stay, MDI scores, and GMQ scores.

[j] High-energy fractures included skull fractures described as complex, branching, comminuted, stellate, diastatic, multiple, bilateral, or crossing suture lines.

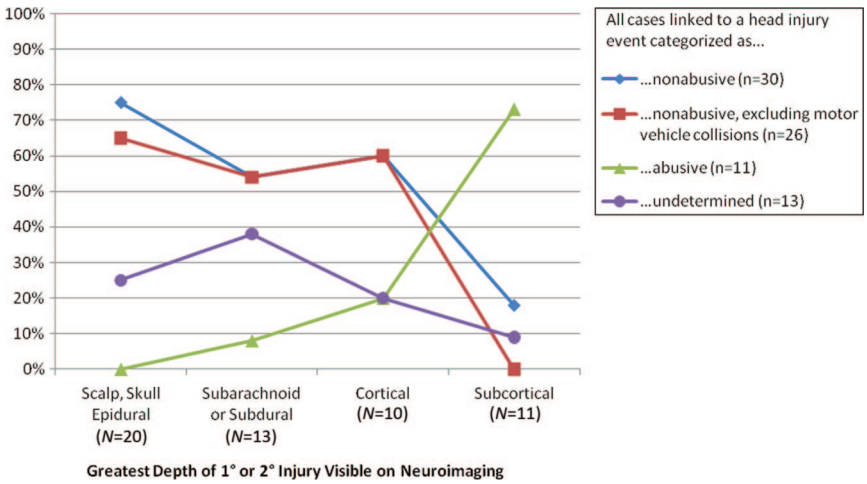

FIGURE 1
Causes of injury for children <3 years of age ($N = 54$) with varying greatest depth of visible, acute, traumatic, cranial injury.

skull fractures were identified for 31 (72%). In contrast, only 4 (36%) of 11 subjects with subcortical greatest depth of visible injury demonstrated craniofacial soft-tissue injuries and only 2 (18%) demonstrated skull fractures.

Twenty-four (44%) of 54 study subjects demonstrated abnormal subdural collections of blood on CT and/or MRI scans. Among the 11 subjects with subcortical greatest depth of visible injury, 7 (64%) demonstrated subdural hematomas (SDHs) categorized as bilateral and 9 (82%) demonstrated SDHs categorized as interhemispheric. In contrast, only 2 (18%) of 11 subjects

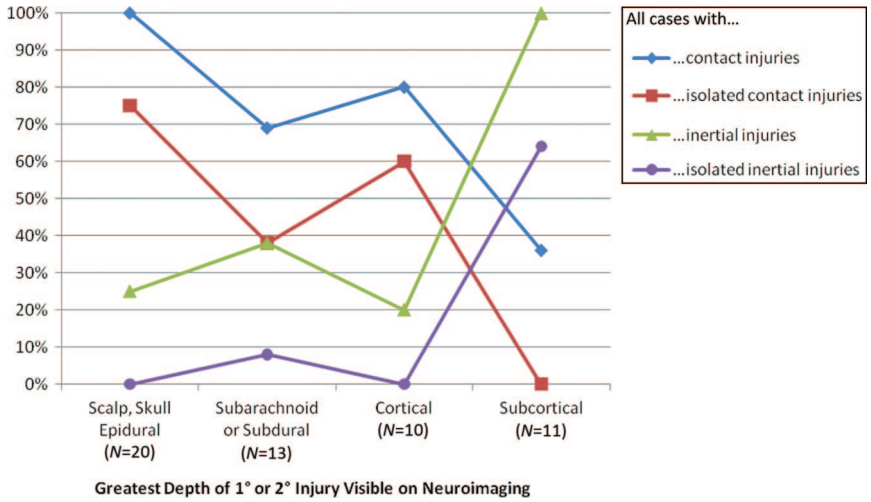

FIGURE 2

Injury mechanisms among children <3 years of age ($N = 54$) with varying greatest depth of visible, acute, traumatic, cranial injury.

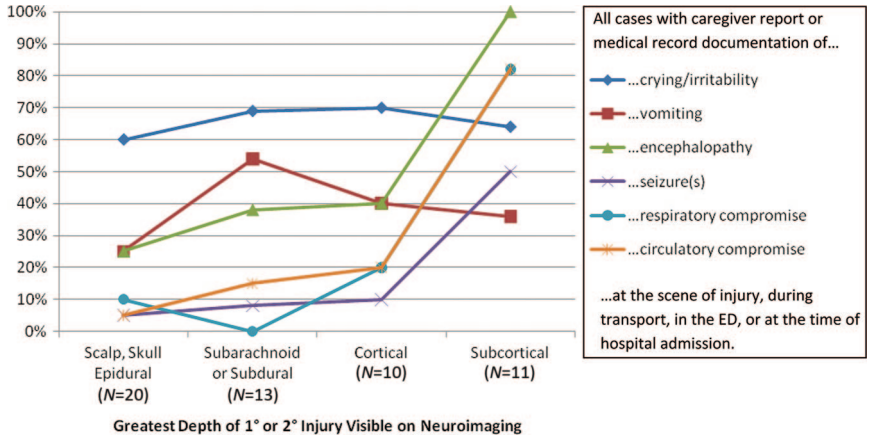

FIGURE 3

Acute clinical presentations among children <3 years of age ($N = 54$) with varying greatest depth of visible, acute, traumatic, cranial injury. ED indicates emergency department.

with subcortical injuries demonstrated SDHs categorized as unilateral and none demonstrated SDHs categorized as small focal. Among the 13 subjects with subarachnoid or subdural greatest depth of visible injury and no visible underlying brain injury, 9 (69%) demonstrated SDHs, including 6 (67%) whose SDHs were categorized as bilateral and/or interhemispheric. Among the 10 subjects with cortical brain greatest depth of visible injury, 3 (30%) demonstrated SDHs categorized as unilateral and 3 (30%) demonstrated SDHs categorized as small focal. In contrast, only 1 (10%) of those 10 subjects demonstrated a SDH categorized as bilateral and none demonstrated SDHs categorized as interhemispheric (Fig 5).

Only 3 (27%) of 11 subjects with subcortical injuries had MDI scores calculated 6 months after injury; each had a score of 50. In contrast, the 23 (53%) of 43 subjects with more-superficial injuries who returned for follow-up neurodevelopmental assessments 6 months after injury had an average MDI score of 97.6 (SD: 12.7). Five (45%) of 11 subjects with subcortical injuries had GMQ scores calculated 6 months after injury. Their average GMQ score was 54.0 (SD: 17.9). In contrast, the 18 (42%) of 43 subjects with more-superficial injuries who returned for follow-up neurodevelopmental assessments 6 months after injury had an average GMQ score of 101.2 (SD: 9.2).

DISCUSSION

In 1974, Ommaya and Gennarelli[25] were the first to propose a specific causal relationship between inertial head injury mechanisms, injury depth, and clinical outcomes. Having observed that isolated inertial loading (ie, rotational cranial acceleration or deceleration) can induce traumatic cerebral concussion, they theorized that traumatic cerebral concussion represents "a graded set of clinical syndromes following head injury wherein increasing severity of disturbance in level and content of consciousness is caused by a mechanically-induced centripetal sequence of disruptive effect on structure and function." In 1997, Levin et al[26] verified that the centripetal theory for traumatic cerebral concussion described by Ommaya and Gennarelli[25] applies to children, linking the severity of impaired consciousness and outcomes to the depth of a child's visible traumatic brain lesions.

In 2001, Geddes et al[22,23] described deep, focal, hemorrhagic and traumatic axonal injuries in the region of the craniocervical junction in infants who died as a result of suspected abusive head trauma. The authors opined that these deep, focal lesions represented primary traumatic injuries capable of inducing acute respiratory and/or circulatory compromise, which could initiate or exacerbate secondary brain injury.

Extrapolating from the work of Ommaya and Gennarelli,[25] we theorized that the deep traumatic cranial injuries observed by Geddes et al[22,23] resulted from inertial injury mechanisms induced by perpetrators'

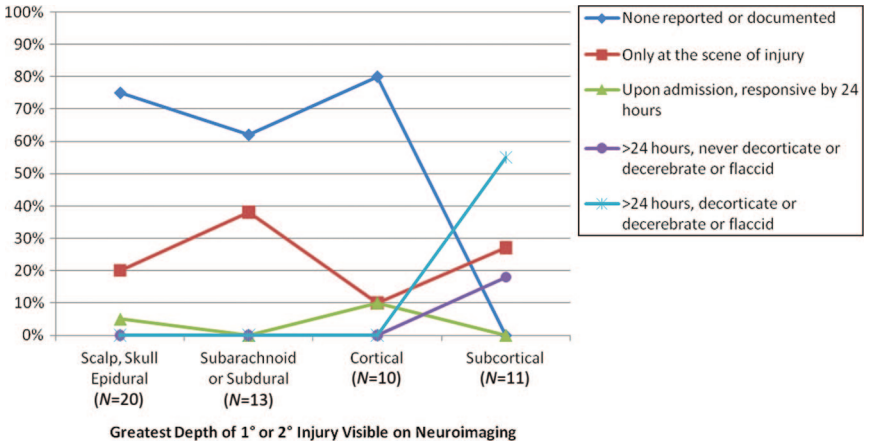

FIGURE 4
Total duration of impaired consciousness among children <3 years of age ($N = 54$) with varying greatest depth of visible, acute, traumatic, cranial injury.

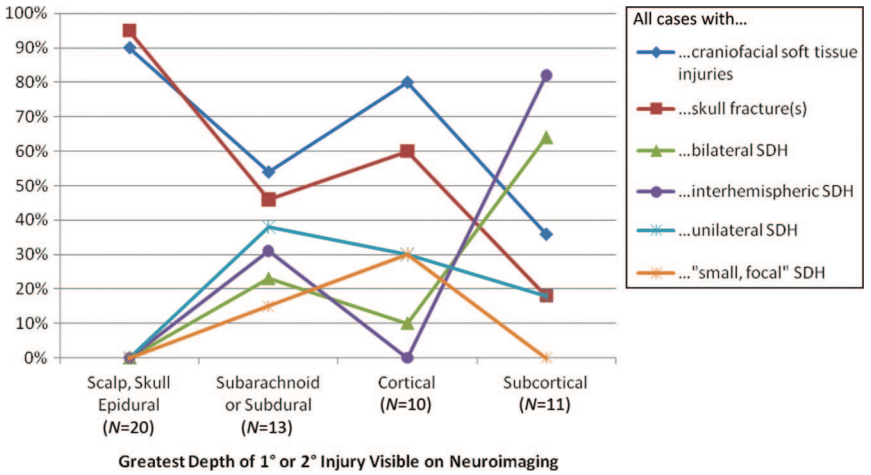

FIGURE 5
Specific primary injuries among children <3 years of age ($N = 54$) with varying greatest depth of visible, acute, traumatic, cranial injury.

abusive actions. In this prospective, multicenter, cohort study, we sought to improve our understanding of these broad pathophysiological relationships by measuring differences in the causes, mechanisms, acute clinical presentations, injuries, and outcomes of children <36 months of age with varying greatest depths of acute cranial injury.

Our results addressing this research objective support several conclusions that have diagnostic, prognostic, and forensic significance. Among infants and young children with closed-head trauma, (1) head injury causes and mechanisms seem to be important determinants of head injury depth, (2) many subcortical brain injuries result from abusive events involving inertial injury mechanisms, (3) in the absence of underlying subcortical brain injury, many more-superficial cranial injuries result from nonabusive events involving contact injury mechanisms, (4) acute and/or prolonged encephalopathy, acute respiratory and/or circulatory compromise, interhemispheric and/or bilateral subdural hemorrhage, and bilateral brain hypoxia, ischemia, or swelling seem to be markers of subcortical brain injury, and (5) patients with traumatic subcortical injuries unrelated to a MVC should undergo thorough evaluation for abuse.

Our study's primary strengths include its prospective, multicenter design; the breadth and depth of data capture; the novel use of fully scripted interviews to facilitate consistent data capture regarding the scene of injury; and the a priori application of criteria for abusive and nonabusive causes specifically designed to minimize circular reasoning and inherent biases. Our study has numerous limitations. Variations in the frequency, timing, and/or modalities of cranial imaging might have affected the validity of our conclusions regarding the greatest depth of visible injury. None of our subjects demonstrated macroscopic (CT or MRI) evidence of primary subcortical injury. Every study subject categorized as having subcortical greatest depth of visible injury demonstrated only secondary brain hypoxia-ischemia or swelling involving the subcortical brain. Our inability to assess reliably the greatest depth of microscopic, primary, traumatic, cranial injuries represents a significant limitation of this study. To address this limitation, we attempted to link presumptive clinical signs of deep, microscopic, primary, traumatic, brain injury (specifically, acute respiratory or circulatory compromise) with our subjects' visible, subcortical, secondary, brain injury. The inherent assumptions in this method might be flawed.

Our schema for categorizing the required mechanisms of injury was based solely on the subjects' cranial injuries that were visible or verifiable. Some of our subjects categorized as having isolated contact injuries might have experienced inertial injury mechanisms that could not be verified. Conversely, some of our subjects categorized as having isolated inertial injuries might have experienced cranial impacts and/or skull deformation that did not produce visible contact injuries.

Our definitional criteria for abusive and nonabusive head trauma causes very likely are imperfect. Only one-half of our subjects underwent follow-up neurodevelopmental assessments. Most importantly, our sample size was small, with significant risk of sampling bias. For all of these reasons, our results should not be overinterpreted. Considered in isolation, this study does not verify a causal relationship between abuse, inertial mechanisms, and subcortical brain injury.

CONCLUSIONS

For infants and young children hospitalized for evaluation and treatment of acute, nonpenetrating, head trauma, assessment of head injury depth facilitates the assessment of head injury causes and mechanisms. Acute encephalopathy, acute respiratory or circulatory compromise, and interhemispheric or bilateral subdural hemorrhage seem to be markers of subcortical brain injury. Infants and young children who demonstrate visible subcortical injuries unrelated to a MVC require thorough evaluation for abuse. These results have diagnostic, prognostic, and forensic significance.

ACKNOWLEDGMENTS

This research was supported in part with resources provided by the National Institutes of Health (grants R21HD043351-01 and R24HD39361-05), the American Academy for Cerebral Palsy and Developmental Medicine, the University of Virginia Children's Hospital Research Fund, and PediBIRN.

In addition to the authors, the following PediBIRN participants and sites made substantial contributions to research project design and data acquisition: Kathy L. Makoroff, MD, University of Cincinnati; Antoinette L. Laskey, MD, MPH, University of Indiana; Carole Jenny, MD, MBA, Brown University; and Suzanne M. Edmunds, MD, Wake Forest University.

REFERENCES

1. Briss PA, Sacks JJ, Addiss DG, Kresnow M, O'Neil J. A nationwide study of the risk of injury associated with day care center attendance. *Pediatrics.* 1994;93(3):364–368
2. Chadwick DL, Bertocci G, Castillo E, et al. Annual risk of death resulting from short falls among young children: less than 1 in 1 million. *Pediatrics.* 2008;121(6):1213–1224
3. Chadwick DL, Salerno C. Likelihood of the death of an infant or young child in a short fall of less than 6 vertical feet. *J Trauma.* 1993;35(6):968
4. Chang A, Lugg MM, Nebedum A. Injuries among preschool children enrolled in day-care centers. *Pediatrics.* 1989;83(2):272–277
5. Duhaime AC, Alario AJ, Lewander WJ, et al. Head injury in very young children: mechanisms, injury types, and ophthalmologic findings in 100 hospitalized patients younger than 2 years of age. *Pediatrics.* 1992;90(2):179–185
6. Helfer RE, Slovis TL, Black M. Injuries resulting when small children fall out of bed. *Pediatrics.* 1977;60(4):533–535
7. Hymel KP, Makoroff KL, Laskey AL, Conaway MR, Blackman JA. Mechanisms, clinical presentations, injuries, and outcomes from inflicted versus noninflicted head trauma during infancy: results of a prospective, multicentered, comparative study. *Pediatrics.* 2007;119(5):922–929
8. Landman PF, Landman GB. Accidental injuries in children in day-care centers. *Am J Dis Child.* 1987;141(3):292–293
9. Leland NL, Garrard J, Smith DK. Injuries to preschool-age children in day-care centers: a retrospective record review. *Am J Dis Child.* 1993;147(8):826–831
10. Lyons TJ, Oates RK. Falling out of bed: a relatively benign occurrence. *Pediatrics.* 1993;92(1):125–127
11. Nimityongskul P, Anderson LD. The likelihood of injuries when children fall out of bed. *J Pediatr Orthop.* 1987;7(2):184–186
12. Plunkett J. Fatal pediatric head injuries caused by short-distance falls. *Am J Forensic Med Pathol.* 2001;22(1):1–12
13. Reiber GD. Fatal falls in childhood: how far must children fall to sustain fatal head injury? Report of cases and review of the literature. *Am J Forensic Med Pathol.* 1993;14(3):201–207
14. Sacks JJ, Smith JD, Kaplan KM, Lambert DA, Sattin RW, Sikes RK. The epidemiology of injuries in Atlanta day-care centers. *JAMA.* 1989;262(12):1641–1645
15. Tarantino CA, Dowd MD, Murdock TC. Short vertical falls in infants. *Pediatr Emerg Care.* 1999;15(1):5–8
16. Williams RA. Injuries in infants and small children resulting from witnessed and corroborated free falls. *J Trauma.* 1991;31(10):1350–1352
17. Willman KY, Bank DE, Senac M, Chadwick DL. Restricting the time of injury in fatal inflicted head injuries. *Child Abuse Negl.* 1997;21(10):929–940
18. Duhaime AC, Christian C, Moss E, Seidl T. Long-term outcome in infants with the shaking-impact syndrome. *Pediatr Neurosurg.* 1996;24(6):292–298
19. Duhaime AC, Durham S. Traumatic brain injury in infants: the phenomenon of subdural hemorrhage with hemispheric hypodensity ("big black brain"). *Prog Brain Res.* 2007;161:293–302
20. Myhre MC, Grogaard JB, Dyb GA, Sandvik L, Nordhov M. Traumatic head injury in infants and toddlers. *Acta Paediatr.* 2007;96(8):1159–1163
21. Zimmerman RA, Bilaniuk LT, Bruce D, Schut L, Uzzell B, Goldberg HI. Computed tomography of craniocerebral injury in the abused child. *Radiology.* 1979;130(3):687–690
22. Geddes JF, Hackshaw AK, Vowles GH, Nickols CD, Whitwell HL. Neuropathology of inflicted head injury in children, part I: patterns of brain damage. *Brain.* 2001;124(7):1290–1298
23. Geddes JF, Vowles GH, Hackshaw AK, Nickols CD, Scott IS, Whitwell HL. Neuropathology of inflicted head injury in children, part II: microscopic brain injury in infants. *Brain.* 2001;124(7):1299–1306
24. Brennan LK, Rubin D, Christian CW, Duhaime AC, Mirchandani HG, Rorke-Adams LB. Neck injuries in young pediatric homicide victims. *J Neurosurg Pediatr.* 2009;3(3):232–239
25. Ommaya AK, Gennarelli TA. Cerebral concussion and traumatic unconsciousness: correlation of experimental and clinical observations of blunt head injuries. *Brain.* 1974;97(4):633–654
26. Levin HS, Mendelsohn D, Lilly MA, et al. Magnetic resonance imaging in relation to functional outcome of pediatric closed head injury: a test of the Ommaya-Gennarelli model. *Neurosurgery.* 1997;40(3):432–440