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Further characterization of traumatic subdural collections of infancy

Report of five cases

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Bilateral convexity and interhemispheric subdural hematomas are common neuroimaging patterns seen in infants who have sustained nonaccidental head injuries (NAHIs). These collections often appear aschronic or acute-on-chronic on computerized tomography (CT) studies. To determine the nature of these extraaxial fluid collections and their relationship to cerebrospinal fluid (CSF) dynamics, the authors studied five infants with suspected NAHI in whom symptomatic bilateral mixed- or low-density subdural collections were revealed on imaging studies; the patients underwent burr hole evacuation of the hematoma and external drainage. Once decompression was achieved, radiotracer was injected into the lumbar subarachnoid space, and the subdural drainage system was monitored for appearance of the isotope. In all five cases, the radiotracer moved rapidly from the lumbar subarachnoid space into the convexity subdural space and then into the external drainage system. This indicated the possibility that some of these mixed-density subdural collections were acute blood mixed with CSF rather than acute-on-chronic collections arising from rebleeding subdural membranes. The authors propose that, during infancy, tears in the loosely adherent arachnoid envelope at the main arachnoid granulation site along the superior sagittal sinus may result in a considerable amount of CSF mixing with acute blood in the subdural space, creating a hematohygroma.

KEY WORDS • subdural hematoma • head injury • pathophysiology • child abuse • shaken baby syndrome • pediatric neurosurgery

NONACCIDENTAL head injury is suspected in approximately 25% of all children younger than 2 years of age who present with head injuries.[18] Caffey[12] coined the term "whiplash shaken baby syndrome" to describe a pattern of infant NAHI associated with vigorous shaking that results in subdural, subarachnoid, and retinal hemorrhages, although it remains controversial as to whether shaking alone is sufficient to cause this.[11,20] The specificity of certain injury patterns for NAHI is also uncertain, but acute or chronic SDHs in an infant in whom the traumatic occurrence is unwitnessed is still highly indicative of child abuse.[9]

Acute SDHs are the most common abnormality detected on neuroimaging in children with suspected NAHI,[6,17] and interhemispheric, convexity, and suboccipital collections are disproportionately associated with abuse when compared to accidental trauma.[28,42,43] Not infrequently, subdural collections of mixed density are present in infants with NAHI, indicating the possibility of multiple episodes of abuse.[28,41,42] The implication of mixed-density subdural effusions is that of repeated abuse, which further confuses issues of timing and exclusive opportunity.[10,17] The evolution of the density and signal characteristics in adult traumatic SDHs[8,25] may not be referable to similar subdural collections in infants with NAHI. Furthermore, there are reports in the literature in which the development of "chronic" subdural collections has been described in children acutely after injury.[17,21,23,28,36] One hypothesis to account for the variable timing and appearance of mixed- or low-density subdural effusions in infant NAHI is that tears in arachnoid and arachnoid granulations result in CSF communication between the subarachnoid and subdural spaces.[4,22,38] We therefore prospectively examined a series of infants with suspected NAHI and SDHs for clinical, MR imaging, and nuclear medicine evidence of free communication between the subdural and subarachnoid spaces.

Abbreviations used in this paper: CSF = cerebrospinal fluid; CT = computerized tomography; DTPA = diethylenetriamine pentaacetic acid; MR = magnetic resonance; NAHI = nonaccidental head injury; SDH = subdural hematoma.

Case Reports

Between 1998 and 2001, five infants presented to the University of Alberta Pediatric Neurosurgical Service with a particular neuroimaging pattern of bilateral subdural fluid collections indicating the possibility of NAHI. Suspicion surrounded the injuries in all cases; no one had witnessed or corroborated any accidental injuries. Investigations included ophthalmological assessment, skeletal survey, and ^{99}Tc bone scanning, and all cases were reviewed by a multidisciplinary team composed of a pediatrician, neurosurgeon, radiologist, and social service representatives. Table 1 summarizes the clinical and radiological features of the five cases.

All five infants were symptomatic and underwent placement of an external subdural drain under direct visualization through a convexity craniostomy hole. Once the subdural collection had been drained and decompressed, an attempt was made to characterize the subdural fluid and predict the required duration for drainage of the subdural fluid by determining its origin and relationship with CSF dynamics. After sedation and injection of a local anesthetic, a lumbar puncture was performed; the patient was placed in the lateral position, with the subdural drain open and draining at a level even with the middle of the head. Approximately 3 ml of CSF was drained; 20 MEq of 111-Indium was injected slowly followed by 2 ml of CSF. Multiple static sequential images at variable time intervals were obtained to follow the flow of radiotracer through the CSF pathways. The external drain was removed when the patient improved symptomatically, CT scanning demonstrated improvement of the subdural collection, and the volume of drainage had decreased significantly.

Four of the five patients underwent cranial MR imaging either pre- or postoperatively. Standard imaging of the brain was supplemented with a dual echo coronal sequence images obtained between the coronal and lambdoid suture in four patients. These studies were all performed on a 1.5-tesla magnet (Symphony; Siemens Medical Systems, Erlangen, Germany) equipped with a head coil. Three- to 4-mm-thick proton density and T_2-weighted (TR 3000, TE 31,120) coronal sequences were obtained with a field of view of 120 mm and a matrix size of 256. A 10% intersection gap was used.

Case 1

This 4-month-old boy was admitted and an elective CT scan was obtained to investigate macrocephaly (occipitofrontal head circumference $>$ 98th percentile). At birth delivery had been assisted by a vacuum extraction device, and the patient's initial head circumference was 35.5 cm (75th percentile). Both parents and the daytime babysitter described irritability, and the child had already been seen several times by the pediatrician. Although the child was generally well, physical examination revealed prominent scalp veins and split sutures. Ophthalmological examination demonstrated no retinal hemorrhages. Cranial CT scanning revealed a widened subarachnoid space and a subdural collection of increased density along the frontal inner table on the left side (Fig. 1 *left*). Skeletal radiographic survey and nuclear medicine bone scanning revealed no fractures. Cranial imaging demonstrated distinct subarachnoid and subdural collections as well as detachment of the arachnoid from the sagittal sinus (Fig. 1 *center*).

A left convexity burr hole was made, and frankly hemorrhagic fluid under pressure was evacuated. Prior to complete drainage of the SDH, an external drain was inserted into the subdural space under direct visualization. No vascular membranes or clots were encountered at the time of surgery. During the subsequent 3 days, drainage volumes from the catheter were 288, 170, and 204 ml, respectively. A nuclear medicine ventricular cisternogram was obtained after injection of 20 MEq of ^{111}In DTPA into the lumbar subarachnoid space after induction of general anesthesia. Within 3 hours, radioactivity was detected in the external catheter tubing and drainage bag, and this was more pronounced by 21 hours (Fig. 1 *right*). The external drain was removed after 3 days, and 1 week later the subdural collection had resolved. At 2-year follow-up examination, he was well with no obvious deficits.

Case 2

This 2-month-old boy presented to the emergency department with a 2-week history of lethargy and a 1-week history of poor oral intake and vomiting. On physical examination we noted that the boy was drowsy, and we observed tense fontanelles, split sutures, right parietal scalp bruising, and bilateral retinal hemorrhages. Cranial CT scanning revealed bilateral mixed-density subdural collections (Fig. 2 *left*). Cranial MR imaging revealed a cephalohematoma, bilateral subdural collections of mixed fluid content, and detachment of arachnoid in the parasagittal region (Fig. 2 *center*).

TABLE 1

Clinical and radiological attributes of five infants with suspected NAHI

Case No.	Age (mos), Sex	Presenting Signs & Symptoms	Acute/Mixed Blood*	Clinical/Skeletal Findings	External Drainage (no. of days)	FollowUp (mos)
1	4, M	macrocephaly	no	none	3	24
2	2, M	lethargy, emesis	yes	bilat retinal hemorrhages, cephalohematoma	4	11 (required subdural shunt)
3	3, M	lethargy, emesis	yes	tibial fracture, bruising	5	10
4	8, M	seizure	yes	bilat retinal femur & tibial fractures, bruising, lacerations	6	11
5	5, F	lethargy, emesis, 6th nerve palsy	no	rib & iliac fractures	5	4

* As demonstrated on noncontrast CT scans.

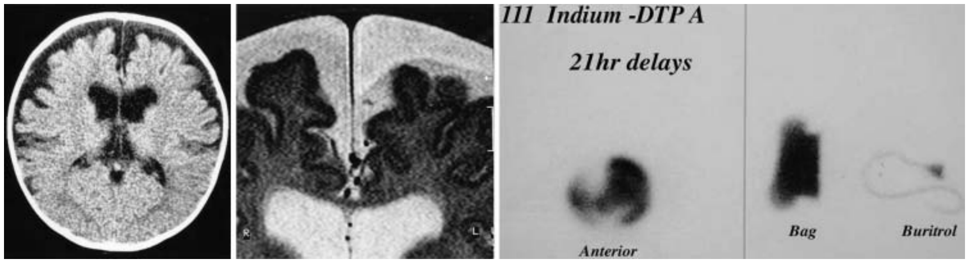

FIG. 1. Case 1. *Left:* Initial axial CT scan demonstrating bilateral frontal hypodense subdural collections in a boy with macrocephaly. *Center:* High-resolution T_2-weighted coronal MR image demonstrating separation of the left arachnoid from its attachment to the superior sagittal sinus, with bowing of the arachnoid laterally. *Right:* Nuclear medicine ventricular cisternogram obtained 21 hours after intrathecal injection of ^{111}In DTPA revealing communication between the subarachnoid space and the subdural external catheter and collection system.

Bilateral convexity burr holes were made to evacuate the hemorrhagic fluid under pressure, but no clots or membranes were seen. Five days later, the child's fontanelles were again tense, and CT scanning demonstrated recurrence of the subdural collections. A repeated right burr hole evacuation was performed, and an external subdural catheter was inserted through the dura into the subdural space under direct visualization. Daily drainage volumes of blood-tinged fluid were 185, 104, 40, and 96 ml, respectively, for the subsequent 4 days. Nuclear medicine cisternography showed drainage of radiolabeled 111-Indium into the drainage bag through the catheter by 24 hours (Fig. 2 *right*). Two days after the external drain was removed, CT scanning demonstrated reaccumulation of subdural fluid that corresponded to deterioration in his neurological status. A right-sided subdural peritoneal shunt equipped with a low-pressure valve was inserted. The patient had an uneventful postoperative course and suffered no obvious neurological deficits 11 months later at the time the shunt system was removed.

Case 3

This 3-month-old boy was taken to the emergency department after paramedics responded to a call from family friends who found the child lethargic and with a large fresh bruise on his face. The boy had a 1-week history of poor oral intake, repeated emesis, and was noted not to be moving his left leg well. Bone scanning and skeletal radiography demonstrated a fracture of the right distal medial tibia. No retinal hemorrhages were seen on ophthalmological examination. On a CT scan we observed bilateral frontal hypodense subdural collections mixed with a small hyperdense collection. The hemorrhagic fluid escaped under increased pressure when a right frontal burr hole was created. An external subdural drain was inserted; the subsequent five daily drainage volumes were 166, 156, 113, 162, and 43 ml, respectively. After removal of the external drain, MR imaging revealed small subdural and subarachnoid fluid collections with CSF density and separation of the arachnoid from the sagittal sinus. Nuclear medicine ventricular cisternography revealed flow of radiolabeled 111-Indium into the shunt tubing and drainage bag by 19 hours. The perpetrator of the abuse confessed, and the child was eventually placed in his mother's care. He was seen again 10 months later because of generalized seizures in the setting of a febrile illness but otherwise had no obvious neurological deficits.

Case 4

This 8-month-old boy presented to the emergency department; a history of a forward fall and seizurelike activity was vaguely sketched. Poor oral intake had been observed for several days, and he had been irritable prior to admission. Examination revealed an ear laceration, bilateral nail bed bruising, bilateral retinal hemorrhages, tight fontanelles, and a head circumference greater than the 90th percentile. Bone scanning and skeletal radiography revealed a minimally displaced transverse left femoral fracture and increased uptake involving the left medial proximal tibia. Cranial CT scanning revealed a right frontal acute SDH and bilateral subdural hypodense collections, and MR imaging demonstrated an acute interhemispheric SDH and bilateral subdural fluid collections. We undertook bilateral burr hole drainage of hemorrhagic fluid without membranes or clot, and a right external subdural drain inserted. Over the next 6 days, before the external drain was removed, 183, 270, 200, 265, 147, and 132 ml of fluid were drained, respectively. A nuclear medicine ventricular cisternogram demonstrated tracer in the drainage bag within 4 hours. A confession was obtained, and the baby was eventually returned to his mother's care. When admitted 3 months later for cast removal, he was progressing well and his head circumference was maturing according to a normal growth curve, although in a somewhat lower percentile level (50th). Eleven months after the injury, on a routine pediatrician visit, he had no obvious neurological deficits.

Case 5

This 5-month-old girl was admitted with a 1-week history of poor oral intake, vomiting, and lethargy. The infant had a full fontanelle, unilateral sixth cranial nerve palsy, and a head circumference well above the 98th percentile. No retinal hemorrhages were identified. Cranial CT scanning demonstrated bilateral extraaxial collections. Skeletal radiography and bone scanning revealed a rib fracture and increased uptake along the left iliac crest. Bilateral burr hole evacuation of the subdural collection revealed hemorrhagic fluid in the subdural space but no

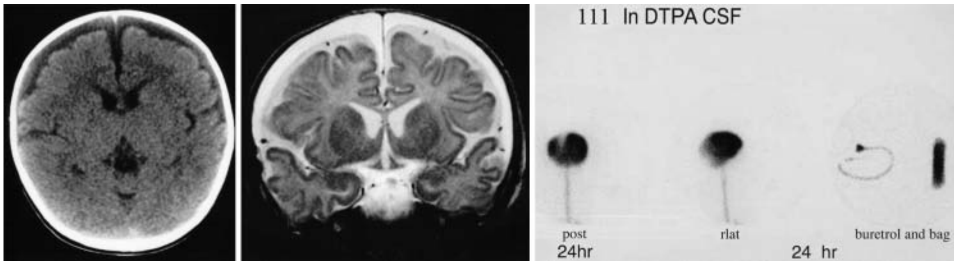

FIG. 2. Case 2. *Left:* Axial CT scan obtained in a boy with lethargy and poor oral intake, showing hypodense extraaxial fluid collections bilaterally over the frontal lobes. *Center:* T_2-weighted coronal MR image revealing bilateral parasagittal subdural collections and arachnoid membrane detached from the sagittal sinus. *Right:* Nuclear medicine ventricular cisternogram obtained 24 hours after intrathecal ^{111}In DTPA injection demonstrating flow of radioisotope out the subdural catheter into the collection system.

membrane formation. An external subdural drain was inserted and during the next 5 days drained 229, 254, 213, 197, and 116 ml, respectively, of fluid. A nuclear medicine ventricular cisternogram demonstrated flow of Indium-111 into the drainage catheter and bag within 4 hours. The baby was placed in her mother's care and had no obvious neurological deficits when seen in the pediatrician's office 4 months later.

Discussion

When confronted with an infant harboring bilateral subdural fluid collections, one must always consider the possibility of NAHI. Subdural hematomas, acute or chronic, are the most common neuroimaging abnormality noted in infants with NAHI and should prompt the physician to search for other signs of abuse such as bruising, fractures, or retinal hemorrhages.[29] Mixed-density and chronic SDHs are less commonly reported than acute SDHs in NAHI.[17,34] The particular pattern noted in this series seems peculiar to early infancy, and these mixed-density collections may result in considerable confusion if used, in isolation, to determine the timing or pattern of abuse. Further complicating the issue of extraaxial fluid collections and NAHI are reports in the literature in which the authors have described the entities of "benign subdural collections of infancy"[35] and "benign enlargement of the subarachnoid spaces"[5]—both of which have been proposed as factors predisposing to the development of SDHs after even minor accidental trauma.[3] A better understanding of the nature of extraaxial fluid collections and their origins in infants with NAHI would serve to address the issues of clinical management and timing of the injury.

This detailed report of five infants with suspected NAHI and the neuroimaging finding of chronic or mixed-density SDH underscores that some of these extraaxial collections may be acute CSF hematohygromas rather than chronic SDH. Free CSF communication between the subarachnoid space and the subdural space was shown in all five cases when ^{111}In radiotracer was detected in subdural catheter tubing within 24 hours of remote intrathecal injection. Furthermore, the volume drained from the subdural catheters frequently exceeded 100 ml/day, and this would be unlikely in cases of isolated chronic SDHs. The formation of chronic SDHs is thought to be due to the traumatic creation of a subdural space by the separation of dural-border cells and the production of a vascular neomembrane.[26] An acute SDH may initially develop depending on the severity of the trauma and degree of hemorrhage during the initial separation of the dural-border cells, but this occurs in the minority of cases[16] and is not a prerequisite for the development of chronic SDHs. Repeated microhemorrhages derived from neomembranes and bridging veins[32] or the effusion of serum from the vascular neomembranes[30,31] results in the progressive enlargement of the subdural collection with blood products. Repeated microhemorrhages or effusions, however, would not be expected to result in the high daily volumes of fluid recorded in our five cases, especially without signs of new bleeding on serial CT scans. Additionally, no membranes were identified at surgery or on MR imaging.

The evidence from our series indicates that NAHI in infants may result in free subarachnoid–subdural communication with resultant subdural hematohygroma formation. We propose a mechanism whereby subdural hematohygromas originate from NAHI (Fig. 3). The acceleration/deceleration of the brain with respect to the dura and skull may result in shear strains at the attachments of the arachnoid envelope to the dura, particularly at the site of the developing arachnoid villi and granulations. Arachnoid villi and granulations consist of capsules of arachnoid cells, fibroblasts, and endothelium connecting a column of arachnoid cells to the venous sinuses.[27] A shear injury across the granulation may disrupt the arachnoid column somewhere along the arachnoid pedicle. Cerebrospinal fluid from the exposed subarachnoid space would thus communicate freely with the subdural space; CSF flow into the subdural space may then strip more arachnoid granulations and propagate the hematohygroma. Arachnoid villi in infants are poorly developed, appearing only as delicate structures on electron microscopy in term infants[24] and not appearing at all until 4 to 6 months of age by standard microscopy.[14] The sagittal and transverse sinuses have the highest density of both bridging veins and arachnoid granulations,[24] and this proposed mechanism of subdural hematohygroma formation may explain the propensity of these collections for the interhemispheric and convexity areas in infants with NAHI.[6,7,43]

The proposed mechanism of shear injury to the arachnoid envelope may explain more than just the CT scanning–documented mixed density of subdural collections and their propensity for the interhemispheric and convex-

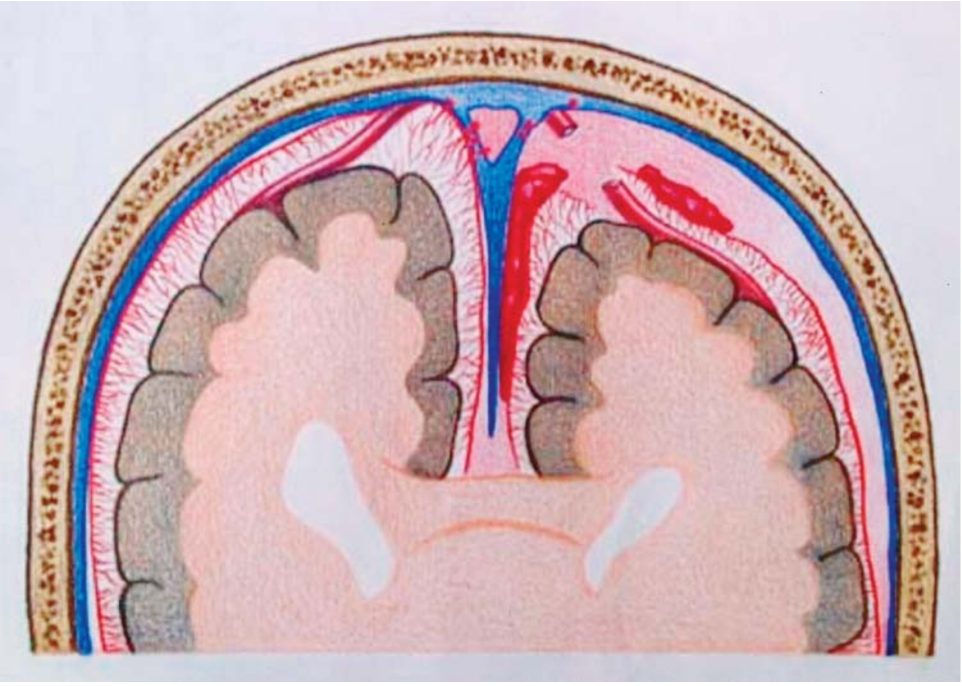

FIG. 3. Diagram. Formation of a subdural hematohygroma. The forces that accelerate/decelerate the brain with respect to the dura separate bridging veins and the weak arachnoid attachments to the parasagittal dura (arachnoid villi and granulations) (shown intact on the left side of the diagram). The resultant arachnoid tear allows CSF in the subarachnoid space to communicate with the newly created subdural space. The mixture of CSF and blood products in the subdural space results in a subdural hematohygroma.

ity spaces. Injury to the arachnoid granulations may also result in suboptimal CSF absorption and subsequent enlargement of the subarachnoid spaces. Enlarged CSF subarachnoid spaces coexistent with subdural hematohygromas are best demonstrated on MR imaging as seen in our series. Specifically, clear separation of the arachnoid envelope from the main CSF absorptive site in the parasagittal region was demonstrated in three cases (Figs. 1 *center* and 2 *center*). Similar MR imaging findings of coexistent SDHs overlying enlarged subarachnoid spaces have been reported elsewhere.[3,33,40] Although enlarged subarachnoid spaces may predispose infants to developing traumatic SDHs, we alternatively propose that enlarged subarachnoid spaces do not necessarily predate the subdural collection but in fact may actually result from the traumatic event. This serves as an additional caution that trauma must always be considered a cause of benign enlargement of subarachnoid spaces in infants. Our finding that chronic or mixed SDHs may dynamically communicate with CSF makes timing estimates of injury based on the imaging appearance of subdural collections alone even more difficult. Duhaime, et al.,[19] have described four children including two infants with rapidly resolving acute SDHs that developed after trauma was witnessed. The authors asserted that CSF communication and washing out of blood products may account for the disappearance of these collections. Dias, et al.,[17] also reported a case of a chronic subdural fluid collection arising shortly after CT scanning initially demonstrated no such findings. Others have reported the presence of chronic subdural collections on initial scans but have interpreted these findings as indicative of remote or repeated abuse.[13,23,36,43] These statements are based on evidence in adults that SDHs evolve in CT scanning–based appearance from acute to chronic during 1 to 4 weeks.[21,41] Recently, however, Vinchon, et al.,[39] reviewed a series of infants involved in witnessed motor vehicle accidents and reported that of seven patients with SDHs presenting within 24 hours of trauma, CT scanning demonstrated hypo- and hyperdense collections in three cases. Furthermore, by the 10th day posttrauma all remaining subdural collections were hypodense on CT scans. The time from the suspected abuse to CT scanning evaluation in our cases could not be determined with certainty, and the possibility of remote or repeated abuse could not be excluded. In each case, however, CSF communication with the subdural space was demonstrated and may have been responsible for the mixed or chronic appearance of a more acutely formed subdural collection. Findings in this case series, combined with the existing literature, indicate that the appearance of the subdural collection alone is not enough to determine the date and time of the injury. Often, other injuries (fractures, bruises, and retinal hemorrhages) provide better timing-related information. The subdural collections certainly strongly suggest NAHI, but these collections are not the most important factor in determining timing or pattern of injury.

Evidence in our study supports the finding extensively reported in the literature[2,6,15,39] that MR imaging is superior to CT scanning for differentiating subdural from subarachnoid collections. In our series, as well in the literature,[3,6,39] clear separation of the arachnoid from the sagittal sinus by a subdural collection was demonstrated. We recommend that infants in whom there are CT findings of chronic SDH or enlarged subarachnoid spaces undergo MR imaging to delineate better the extraaxial spaces. The finding that the arachnoid envelope is detached from the sagittal sinus should suggest the possibility of a dynamic CSF hematohygroma of traumatic origin. Although it has been asserted that CT scanning may be more sensitive in the initial evaluation of child abuse and that MR imaging should be performed 5 to 7 days after injury,[1] Suh, et al.,[37] demonstrated that early diffusion-weighted MR imaging was more sensitive in detecting white matter injury and predicting outcome than standard MR imaging. Clearly more work relating the timing of head injury to the MR imaging patterns and appearances is needed.

The current study and much of the literature on NAHI is limited by a lack of reliable clinical history to support the timing and mechanism of the injuries. The less dramatic clinical presentation as well as the good early clinical outcome observed in each of our cases suggests that the trauma inflicted did not cross the major brain injury thresholds seen in some other series of NAHI. This indicates that subdural hematohygromas can be the result of forces occurring at the lower end of a continuum of inflicted violence and with a subsequent lesser degree of cerebral injury sustained by the victim. Because the details of such injuries rarely surface, however, this hypothesis is difficult to test.

Conclusions

Our case series of infants with suspected NAHI in whom chronic SDH is demonstrated on CT scanning indicates that these lesions are dynamic CSF hematohygromas. Cerebrospinal fluid communication with these subdural collections was shown by the rapid flow of high volumes of radiotracer from the lumbar subarachnoid cistern into subdural catheters. Obvious detachment of the arachnoid envelope from the sagittal sinus was observed on MR imaging, suggesting that attachments of the arachnoid granulations to the venous sinuses are prone to separation in infants sustaining NAHI. The attachment of arachnoid villi and granulations becomes more secure and the skull less distensible as the child grows, possibly explaining the rarity of this hematohygroma finding in older children and adults. In the setting of head injury in early infancy, a CT scanning–documented mixed-density or hypodense SDH may not be chronic but may actually be an acute hematohygroma of mixed CSF and blood. Subdural fluid collections in infancy should always raise concerns about abuse, but the confusing imaging characteristics of these subdural collections make them unreliable for predicting the timing of the injury. Associated osseous injuries and injury to the eyes or soft tissues may provide more reliable information as to when the abuse occurred.

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