Common Data Elements for Neuroimaging of Traumatic Brain Injury: Pediatric Considerations

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Abstract

As part of the Traumatic Brain Injury Common Data Elements project, a large-scale effort to define common data elements across a variety of domains, including neuroimaging, special considerations for pediatric patients were introduced. This article is an extension of that initial work, in which pediatric-specific pathoanatomical entities, technical considerations, interpretation paradigms, and safety considerations were reviewed. The goal of this review was to outline differences and specific information relevant to optimal performance and proper interpretation of neuroimaging in pediatric patients with traumatic brain injury. The long-range goal of this project is to facilitate data sharing as well as to provide critical infrastructure for potential clinical trials in this major public health area.

Key words: CT; common data elements; MRI; pediatrics; traumatic brain injury

Overview and Rationale

THE TRAUMATIC BRAIN INJURY COMMON DATA ELEMENTS project was designed to standardize data collection and facilitate data sharing across a wide range of patient and injury variables and at varying intervals after injury (Thurmond et al., 2010). This large-scale initiative provided recommendations for common data elements (CDE) for traumatic brain injury (TBI) across a variety of domains, including neuroimaging. In the first phase of the initiative, recommendations for TBI neuroimaging CDE were formulated by a multidisciplinary panel of experts through an iterative process of scientific review. In the second phase of the initiative, a multidisciplinary review of those CDE was conducted with a focus on identification of elements that are appropriate to the pediatric population. The pediatric neuroimaging work group included professionals with expertise in basic imaging research and physics, clinical neuroradiology, and neurosurgery. Further information regarding the background of the TBI CDE initiative and the methods used by all workgroups to arrive at CDE recommendations is detailed by Hicks and associates (Hicks et al., 2011).

To optimally characterize neuroimaging elements for children, age-dependent features must be considered across a number of realms within neurotrauma. These include differences in injury mechanisms and injury types typical for each age; specific technical considerations based on differences in size, physiology, and other relevant parameters; age-dependent differences in image characteristics of normal

children, which must be understood for accurate interpretation of images in the setting of trauma; and age-specific imaging safety and procedural considerations. For these reasons, pediatric neuroimaging CDE need to include appropriate diagnostic entities, imaging protocols, and interpretation schemes for infants and children of different ages.

In the recently published article on Common Data Elements for Neuroimaging, and posted on the NIH/NINDS Common Data Elements web site, two sets of elements are provided as Appendices (Duhaime et al., 2010). (<http://www.commondataelements.ninds.nih.gov/TBI.aspx>). The first (Appendix I) is a list of the pathoanatomical entities present in patients with TBI, from the acute stage to the more chronic stage, with standardized operational definitions based on objective findings and descriptions. The second cluster of elements (Appendix II) involves technical parameters for acquiring standard images, using CT and MRI. Although care was taken to include basic pediatric entities within those elements, in this article we provide an overview of the various additional considerations for CDE and optimal implementation in neuroimaging of TBI in the pediatric population.

Pediatric Traumatic Pathoanatomical Entities

Children may incur injury from different mechanisms than adults, including non-accidental trauma in infancy, crush injuries from static loading in toddlers and young children (most often being run over by vehicles, or pulling heavy

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objects onto the head), and various age-related sports and recreational injuries. In addition, because the pediatric skull is more malleable, and the mechanical properties of the head, neck, and other anatomic structures differ from those of adults, the resultant injuries from a given scenario reflect the unique interplay of the mechanism and the host response. For example, infants and toddlers may sustain so-called "ping pong fractures" in which the bone is pushed in at a site of focal impact but not fractured through both bony tables. Similarly, brain lacerations may occur underlying a linear skull fracture line, even if the fracture edges are not significantly displaced on imaging, because the malleable bone deforms transiently and then returns to its prior form. Finally, differences in cerebral physiology, such as higher cerebral blood flow, ongoing rapid growth, and changes in myelination all may affect the brain's response to injury and how it evolves and appears on imaging. All of these differences may result in pathoanatomical entities that are unique or at least more common in children than in adults.

When creating a list of the various pathoanatomical entities associated with TBI, the authors of the recently posted appendices to the article cited previously included elements that commonly occur in pediatric patients. These radiologic data elements are described and defined operationally so that a researcher entering data should be able to find the relevant neuroimaging findings seen in children of all ages on conventional CT or MRI. Patterns of acute subdural hematoma with associated hemispheric hypodensity, as occur most commonly in infants and toddlers, were included, as were indeterminate and mixed extra-axial collections, diastatic skull fractures, and ping-pong fractures. Enlarged extra-axial cerebrospinal fluid (CSF) spaces, the need for head circumference percentiles in interpreting images, and age-dependent differences in normal cisternal appearance were discussed. Injuries to the cervicomedullary junction, which may occur from distracting forces in vehicular crush injuries in preschool-aged children, were described.

With respect to using CDE for studies involving patients in the more chronic stages of recovery, researchers may need to take into account a potentially different and more prolonged time course of these processes in children compared to adults (Alberico et al., 1987; Filley et al., 1987; Kriel et al., 1988; Luerssen et al., 1988; Mahoney et al., 1983). Therefore, the timing of both follow-up imaging and functional outcome measures might need to take these differences into account.

Different Technical Considerations

With respect to pediatric-relevant pathoanatomical entities, the Pediatric Neuroimaging working group recommends that the previously published list of general pathoanatomical entities be used, as these were specifically designed to include entities encountered throughout the entire age spectrum. In contrast, with respect to pediatric considerations in imaging acquisition, separate protocols specific to children of different ages are appropriate for CT and MRI.

For CT, radiation dose is of particular importance in the pediatric population, as mentioned in the subsequent Safety and Procedural Considerations section. Dose reductions for head CT examinations can be achieved by age-specific or

weight-specific guidelines. The Alliance for Radiation Safety in Pediatric Imaging has sponsored the "Image Gently" campaign, which has a web site that provides general information about how to lower radiation dose when imaging children (www.imagegently.org). Calculating accurate radiation doses usually requires the skills of a radiation physicist, who can work with the radiologists and technologists to tailor imaging parameters to the age or size of the child. CT scanner manufacturers (of which there are several) have developed automated dose-modulation techniques to assist in the selection of appropriate parameters. These can be used to dynamically control the tube current (mA) during scanning, based on user settings and adapted to the body geometry seen on the scanogram. Unfortunately, the modulation technique and settings used differ considerably among vendors (Nievelstein et al., 2010), such as Smart Scan (GE Healthcare, Waukesha, WI), Dose Right (Phillips Medical Systems, Cleveland, OH), CARE Dose 4D (Siemens Medical Solutions, Forchheim, Germany), and Sure Exposure (Toshiba Medical Systems, Otawara-Chi, Japan).

As a guideline, we have included in Appendix II (technical parameter information) of the CDE web site examples of pediatric head CT imaging protocols, which are categorized by age (<http://www.commondataelements.ninds.nih.gov/TBI.aspx>). The tube voltage (kVp) and tube current (mA) are lower in the younger/smaller patients and gradually increase with age/size. If iodinated contrast is required for CT angiography or CT perfusion, the doses are calculated by weight, which is the same as for adults. However, the injection rate is slower, to account for smaller veins (and resulting smaller intravenous cannulas). In addition, the delay between injection and scanning is shorter, to account for faster circulation times in children.

With respect to MRI in the pediatric population, there is no risk of radiation, and the protocols generally do not have to change, unless there is a need to shorten the scan time. Most current conventional MRI sequences already incorporate methods for shortening the time needed for MRI data acquisition, such as "fast" or "turbo" techniques. Advanced sequences, such as diffusion-weighted imaging, also use ultra-fast methods such as echo-planar imaging (EPI). However, in an unsedated or poorly sedated patient, MRI parameters can be significantly modified to reduce scan time. Rapid MR sequences that have been developed in fetal imaging of the brain and spine can be used in these situations (Glenn and Barkovich, 2006). Some MRI sequences are specifically designed to be rapid, sacrificing some degree of resolution, such as the half-Fourier single-shot turbo spin-echo (HASTE) technique. This is a very rapid T2-weighted sequence that can be used in children to replace a conventional T2-weighted sequence (Penzkofer et al., 2002).

Certain MR sequences, such as diffusion-weighted or tensor imaging, may need to be adjusted to account for higher water content in the less myelinated, developing/maturing brain (Miller et al., 2003; Mukherjee and McKinstry, 2006; Mukherjee et al., 2001, 2002). For example, diffusion weighted imaging in infants <1 year of age may be best with a maximum b value of 800 sec/mm². In addition, analysis of diffusion parameters or brain metabolites in MR spectroscopy requires knowledge of age-related changes as the pediatric brain develops (Girard et al., 2007; Schneider et al., 2004). Examples of imaging protocols that are specific for children of

different ages can be found on the CDE website at (<http://www.commondataelements.ninds.nih.gov/TBI.aspx>).

Interpretation of Pediatric MRI

As with many other aspects of pediatrics, the aphorism that “children are not little adults” holds true for imaging. Because of rapid changes in brain anatomy and physiology, age-matched normative data are necessary for accurate interpretation of MRI for any diagnostic category. To this end, the National Institutes of Health (NIH) has sponsored a project to collect and provide data on age-related normative changes on MRI (<https://nihpd.crbs.ucsd.edu/nihpd/info/index.htm>).

Several specific instances of brain maturational differences are relevant to MRI findings in trauma. In infants <1 year of age there is a very wide range of normal extra-axial CSF space around the brain. Therefore, prominent extra-axial CSF spaces should not be ascribed to atrophy unless there is proof positive of brain volume loss on serial imaging, or a positive history of known causes of atrophy such as congenital HIV or a definitive history of prior head trauma. Serial measurements of head circumference, as a surrogate for brain growth, can be extremely helpful in confirming or refuting the presence of volume loss. The presence of macro- or microcephaly is a valuable piece of information as it will guide the neuroradiologist toward two very different diagnostic pathways.

Because of the lack of myelination of the cerebrum, even in a full-term neonate, certain T2-weighted sequences such as fluid-attenuated inversion recovery (FLAIR) may be less helpful in the newborn period; therefore, a balanced or proton density sequence may be better able to detect white matter abnormalities. Even a T1-weighted sequence may be helpful in identifying white matter injury in a young infant, and because of the small head size, three-dimensional (3D) imaging may be beneficial in improving the visuospatial resolution in the neonate. Greater care may need to be taken in the interpretation of diffusion-weighted imaging (DWI) in the newborn, as there have been reports of restricted diffusion changes, resulting from an ischemic insult, resolving before 10 days in premature infants and newborns. Normal myelination, in the corticospinal tracts for example, may show as T2 bright signal change with “shine-through” on DWI and, as in older children and adults, it becomes important to correlate with the apparent diffusion coefficient (ADC) maps (see Appendix II for a list of abbreviations, definitions, and more detail on these various sequences, <http://www.commondataelements.ninds.nih.gov/TBI.aspx>).

MR spectroscopy demonstrates a different pattern of metabolites in early infancy compared to the adult brain. Whereas creatine tends to be fairly stable, the *N*-acetyl aspartate (NAA) peak in normal infants starts lower than that of choline but rises rapidly with myelination during the first 6 months of life, whereas the choline peak demonstrates a relative diminution in height. Lactate may normally be present in trace amounts during the first 24 h after delivery, but the presence of a measurable lactate peak after the first day of life is abnormal and other etiologies such as hypoxic-ischemic injury should be sought.

Hemorrhage in the newborn period may be related to the trauma of a normal birthing process if subdural blood is restricted to the posterior fossa. This typically resolves by 1 month of life. In a similar fashion the presence of fluid within the mastoid air cells and middle ear clefts may be a normal finding up to 1 month of life but should be cleared thereafter.

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Safety and Procedural Considerations

Although safety is a consideration with all patients undergoing CT and MR imaging examinations, special considerations must be made when pediatric patients are going to be imaged. For children with TBI, the first examinations ordered in the emergency department will often involve radiation exposure including CT and plain radiographs. CT provides the major portion of radiation exposure within diagnostic imaging, accounting for ~ 67% of radiation exposure in only 11% of the total diagnostic procedures (Amis et al., 2007). Radiation dose is of particular importance in the pediatric population, because children’s maturing organ systems are more radiosensitive than those of an adult; therefore, the potential for expression of radiation-induced biological effects later in life is a primary concern (Brenner and Hall, 2007). As a result, reduction in dose while maintaining diagnostic image quality is an increased focus of many groups including the Image Gently Organization (Goske et al., 2010; Strauss et al., 2010), the American College of Radiology (ACR), the American Association of Physicists in Medicine as well as CT manufacturers (Strauss et al., 2009). Major reductions in dose can be achieved by tailoring the examination to the clinical indication, and then performing it with a child-appropriate technique. CT manufacturers in response to demand and government regulations have developed protocols, and will provide information for pediatric dose reduction appropriate for their scanners. In children, the possibility of motion during the study must also be considered, as the radiation dose will be doubled if the examination must be repeated. Adequate immobilization and/or sedation are also considerations before exposing a child to ionizing radiation. Sedation providers must comply with protocols established by the individual state and institution with adherence to standards of care mandates following the sedation guidelines developed by organizations such as the American Academy of Pediatrics (1992, 2002).

With the increased use of higher field MR scanners, there is also increased risk for all patients, healthcare professionals working with the patients, and family members accompanying the patient. In addition to routine medical chart and image review, it is best to do MR safety screening of children with the cooperation of the parents or guardians if possible. Metal detectors can be used to screen toys or stuffed animals that children may want to take into the scanner. A recent featured article from the Radiologic Society of North America (RSNA) states that the 2008 Food and Drug Administration (FDA) accident report data show a 310% increase in MRI-related accidents since 2004 (Radiologic Society of North America, 2010). Most accidents are a result of “projectile” injuries in which ferromagnetic objects are strongly attracted to the magnetic field and consequently accelerated toward the bore of the magnet at a high speed, putting the patient, or anyone standing near the bore of the magnet, at risk for being hit by the resulting “missile”. Burn injuries to patients are also common, and result from conductive materials such as cables

or electrodes on radiofrequency coils, and physiological monitoring equipment that can heat up during gradient pulsing. MR-contraindicated implantable devices, such as cardiac pacemakers, cardioverter/defibrillators, or deep brain stimulators, although not as common in pediatric patients, must be screened for in personnel or family members who enter the MR suite. Vagus nerve stimulators require special considerations as well, as transmit-receive coils are required, and the device must be turned off before the scan, according to the manufacturer. Cochlear implants historically have not been considered MR compatible, but MR-compatible cochlear implant devices are under development. Deep brain stimulators are technically considered MRI incompatible, but some experience has accrued in some centers with MRI at 1.5 T for the electrodes only, before they are attached to the generator; for specifications, the manufacturer of the individual devices should be contacted for guidance. Another commonly used implantable device in children is the programmable shunt, which may be unintentionally changed by the magnetic field leading to over- or under-drainage of CSF. For these children, a trained programmer or clinician must be available to verify the correct setting, and reprogram the device if necessary following an MR scan at any field strength. A resource that can be used to aid MR personnel in determining whether implants or devices are safe for MR imaging is the web site (MRIsafety.com). In addition, many manufactures have MR safety information posted online or will email or fax information regarding the MR compatibility of their devices if contacted. Toll-free numbers are usually available online. For help in establishing a safety program for MR departments, an American College of Radiology committee has published useful guidelines for safe MR practices (Kanal et al., 2007). In addition, a web site is available with MR safety information at (www.imrser.org).

Sedation for the pediatric patient is more common for MRI than for CT, because of the longer imaging times. Earplugs or headphones to decrease acoustic noise should be used on all pediatric patients even if sedated. For neonates and younger infants, FDA-approved body temperature monitoring equipment is available to prevent hypo- or hyperthermia while in the MR scanner (Bryan et al., 2006). For toddlers and older children, many hospitals have an MR safe system to allow children to watch videos while being scanned. This is appropriate depending upon the child's age, ability to cooperate, and level of injury. Otherwise, sedation with appropriate monitoring using only MR-safe equipment is necessary to obtain images without motion artifacts. Several manufacturers make FDA-approved, MR-safe, patient monitoring equipment, anesthesia equipment, and ventilators. Care must be taken to avoid taking non-MR safe equipment, including smaller items such as scissors, stethoscopes, or clipboards, into the magnet suite to avoid injury to the patient caused by burns or projectiles. MR safety training for non-MR hospital personnel such as nurses, respiratory therapists, or anesthesia personnel working in the MR suite to monitor patients should be mandatory. Posted signs, warnings, and metal detectors should not be a substitute for MR safety education.

Conclusions

Neuroimaging for children with TBI can be performed and interpreted optimally when attention is given to age-

dependent differences in injury type, use of appropriate imaging parameters, proper age-dependent interpretation, and safety precautions. These considerations are necessary to insure appropriate inclusion of patients of all ages in CDE efforts, and should lead to improved data collection and research in pediatric TBI. It is clear that as with all technologic advances in medicine, changes will occur rapidly. Further considerations regarding emerging technologies and pediatric applications are provided by Hunter et al. (in press).

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