Head Computed Tomography Scanning During Pediatric Neurocritical Care: Diagnostic Yield and the Utility of Portable Studies

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Abstract

Background We report our use of portable head computed tomography (CT) and the diagnostic yield and radiation dose from head CT in the pediatric intensive care unit (PICU).

Methods 204 PICU patients underwent head CT during 2008–2009. Therapeutic interventions and resource intensity during CT were categorized. Severity of illness was summarized using the pediatric risk of mortality (PRISM-III) model. Estimates of patient radiation dose were based on dose measurements made in four anthropomorphic head phantoms.

Results 242 (62%) out of 391 head CT studies were portable. New pathology was identified on 80 (40%) scans. CT findings prompted a change in management in 46 (23%) patients; 25 of these resulted in life-extending treatments and 21 had forgoing of life-sustaining treatments within 24 hours. 26 patients with PRISM score greater than 30% underwent CT; 23 (88%) of these were portable. More portable versus fixed examinations were performed in patients requiring extracorporeal membrane oxygenation, inhaled nitric oxide, high levels of positive end expiratory pressure, and those with high vasopressor scores ($P < 0.05$). Estimated patient dose from portable CT was $83 \pm 6$ mGy compared to $72 \pm 5$ mGy for patients imaged on a fixed scanner ($P < 0.0001$).

Conclusion Two-thirds of CT scans obtained in the PICU were portable because of patients’ intensity of therapy and illness severity. Portable CT showed major new pathology in greater than 1/3 and led to a change in management in 1/4 of higher acuity patients scanned. The estimated radiation dose from portable CT is within the current national guidelines.

Keywords Computed tomography · Bedside · Portable · Radiation · Children · Neurocritical care · Critical illness

Introduction

Head computed tomography (CT) imaging is a central component of the initial assessment and management of patients with acute brain insult. The identification of new pathology or a lesion requiring surgery is paramount for time-critical interventions. In neurocritical intensive care unit (ICU) practice in adults, the introduction of portable head CT imaging has provided a further dimension to care: the possibility of obtaining a more complete diagnosis by bringing the technology to the patient’s bedside at a time when transfer of critically ill patients with high acuity to the radiology imaging suite may not be feasible [1–4].

Previous reports in the literature have found that portable head CT provided acceptable image quality in the ICU environment [3, 5–8]. An advantage of portable
imaging is the reduced need for intrahospital transport. Transport of critically ill patients can be hazardous: in critically ill adults, adverse events are reported between 20 and 70% of transports to radiology [4, 9] compared to less than 4.3% adverse events with portable CT imaging [1, 2, 4, 7, 10]. For critically ill children, studies have found a deterioration in physiologic variables in up to 72% of transports to the radiology suite [10–12]. A disadvantage of CT is the risk of radiation exposure. The recent dramatic increase in CT imaging in the pediatric population has raised concerns that there could be an increased lifetime attributable risk of radiation induced cancer in children compared to adults [13, 14]. To our knowledge, there are no prior reports of the organ dose (i.e., to directly irradiated brain tissue) from portable head CT imaging in children.

Portable head CT imaging has become common practice in adult neurointensive care in the past few decades. In children, there are no published reports about the use of this technology. Four years ago, our center introduced portable head CT imaging capability in the pediatric intensive care unit (PICU) setting. We undertook this retrospective study to present our experience; to assess the overall diagnostic yield and effect on patient management of head CT scanning in critically ill patients in the PICU; to examine patient factors that are associated with the method of CT obtained; and to determine the radiation dose to the patient from both portable and fixed head CT imaging.

Methods

Design, Setting and Patients

The hospital electronic medical records were searched for those individuals who underwent head CT scanning as determined by the critical care attending or consulting neurologists and neurosurgeons during admission to the cardiac or combined medical/surgical PICUs at Children’s Hospital Boston between February 2008 and December 2009 (22 months). The study period represents the second year after introduction of the portable CT scanner, by which time both units were consistently using this technology. Both PICUs are 30 bed, closed panel units in which the critical care physicians are responsible for all patient care. Patients who had a head CT performed while in the operating room, emergency room or on the ward were excluded since the purpose of this study was to evaluate the use of head CT imaging in the PICU and its impact on clinical decisions for these patients. The subjects were divided into two groups, “portable” and “fixed,” based upon the type of CT scan performed during admission. The Institutional Review Board approved this study with waivers for study of retrospective data.

Data Extraction

The critical care attending and fellow daily notes were reviewed by an investigator trained in both neurology and pediatric critical care (KLL) for clinical indication for the CT study, radiographic findings and change in patient management that followed the first head CT scan. For clinical indication, the single most relevant new onset neurologic sign, symptom or presenting problem that led to the decision to order a CT study was recorded. The final report of the CT scan was used to confirm the presence or absence of new brain pathology. The radiographic findings were grouped into the following categories: intracranial hemorrhage, cerebral edema, infarction, anoxic injury, ventriculomegaly/hydrocephalus, and other/nonspecific. Any change in patient management that occurred both as a result of the CT findings and within 24 hours after the CT scan was performed was recorded. A change in patient management consisted of the following: new brain-directed measures, such as the administration of 3% hypertonic saline or 20% mannitol, institution of hypothermia, blood pressure augmentation for maintenance of cerebral perfusion pressure or elevation of the head of bed; a cancelled operation; the decision to discontinue extracorporeal membrane oxygenation (ECMO) support; the documentation of a new resuscitation status; a neurosurgical operative intervention; and the decision to withdraw or withhold treatment.

Patient severity of illness was quantified according to the pediatric risk of mortality-III (PRISM-III) model [15] with data recorded from the first 24 hours of admission as part of this research study. Bedside therapies provided at the time of the first head CT study were categorized according to the intensity of respiratory, cardiac and other organ-specific care. For respiratory parameters, the level of positive end expiratory pressure (PEEP) or mean airway pressure (MAP) for those on high frequency oscillatory ventilation (HFOV) as well as the use of inhaled nitric oxide (iNO) were recorded. The cardiovascular parameters of interest were the total inotropic support as described by the Wernovsky vasopressor score [16] and the use of ECMO. In regards to other high-intensity therapies, we noted the use of renal support with continuous venovenous hemofiltration (CVVH) and the presence of unstable intracranial pressure (ICP) as defined by a level above 20 mm Hg requiring treatment.

Portable Head CT Imaging

The portable head CT device is a commercially available, FDA-approved scanner (CereTom®, Neurologica, Danvers, MA) [17]. We have used this device since March 2007. This portable machine is stationed in one of the PICUs, but it is available to all departments. All patients undergoing
portable head CT are examined at the bedside, and they are not transported to a special imaging suite on or off the unit. A trained group of radiographers qualified to operate CereTom® are available 24 hours/day, 7 days/week.

Estimated Patient Dosimetry

Patient radiation dose was estimated from direct measurements of the radiation energy emitted by the CT scanner into a standardized phantom. This CT dose index (CTDI) phantom is a cylinder 16 cm in diameter with a length of 15 cm constructed of polymethyl methacrylate. The CTDI_{100} is a dose index measured at the surface and center of the CTDI phantom with a calibrated pencil ionization chamber 100 mm in length. CTDI_{vol} is the amount of radiation produced by the CT scanner, which allows for comparison of the radiation generated by two different CT scanners; it is not an estimate of patient dose. CTDI_{vol} estimates the average radiation dose to an axial slice of the CTDI phantom, and it has a unit of milliGray (mGy).

The effective dose, which has units of milliSieverts (mSv), is defined as the whole body dose delivered to the patient that results in the same risk to the patient as the actual clinical dose that is delivered to only a fraction of the patient’s whole body. While the effective dose allows one to estimate risk to a population of patients, it does not provide radiation dose estimates to the directly irradiated tissues (e.g., brain) of an individual patient undergoing head CT. The estimated patient organ dose to these tissues, which adjusts for the individual size of the patient was based upon dose measurements made with the 100 mm pencil ionization chamber in four anthropomorphic head phantoms ranging in size from a newborn to adult head within the CT scanners used in this study. The anthropomorphic phantoms are elliptically shaped and constructed of tissue-equivalent plastic to represent soft tissues with a different surface plastic selected to mimic the attenuation properties of a patient’s skull.

Statistical Analysis

The Statistical package for social sciences (SPSS version 19.0 for Windows, SPSS Inc., Cary, NC) was used for descriptive statistics. Categorical variables were compared using one-sample chi-square test, Fisher’s exact test or the binomial test for comparing two proportions. Continuous variables were compared using independent samples t tests; equal variances were not assumed. When normality assumptions about the data were suspect, the Mann–Whitney U-test was used to compare the medians of two groups. All P values are two-tailed and considered significant if P < 0.05.

Results

PICU Head CT Utilization and Head CT Findings

Over the 22 month period, a total of 204 patients out of 6766 ICU admissions received 391 head CT studies; 242 (62%) of these studies were obtained by the portable CT device. Only the first PICU admission was studied for five patients with multiple admissions that met inclusion criteria. Sixty-eight (33%) patients had studies in the radiology suite (“fixed group”) and 136 (67%) had a portable CT scan (“portable group”). The median age of patients undergoing imaging was 5 years (range 0.8–15 years). The two groups did not differ in age, gender or indications for CT.

The relationship between clinical indication for the CT examination, head CT findings and impact of the study on patient management is shown in Fig. 1. Two hundred patients had data that were able to be evaluated. The other four patients had indeterminate findings on CT. One hundred thirteen of the 200 patients had signs or symptoms warranting imaging, including change in mental status (n = 34), pupillary change (n = 28), seizure (n = 38) or other neurological sign or symptom (n = 13) (Fig. 1a). The other 87 of the 200 patients had a clinical condition that warranted imaging, such as cardiac arrest (n = 29), known previous lesion requiring follow-up imaging (n = 28), other medical condition (n = 20) or recent neurosurgical operative intervention (n = 10) (Fig. 1a). Eighty (40%) of the 200 patients had previously undiagnosed brain pathology on CT scan (Fig. 1b). Since no difference was seen between the portable and fixed groups for signs/symptoms, clinical indication and diagnostic yield, the results from both groups were combined in Fig. 1.

Previously undiagnosed radiological findings on head CT included intracranial hemorrhage, cerebral edema, cerebral infarct, features of anoxic brain injury and worsening ventriculomegaly or hydrocephalus. The most common new radiological diagnosis on head CT was intracranial hemorrhage in 24 (12%) patients, followed by cerebral infarct in 15 (8%) and cerebral edema in 14 (7%). There was no difference between portable and fixed groups for radiologic diagnosis. Forty-six (23%) of the 200 patients undergoing CT examination had a new intervention prompted by new CT findings: 25 (54%) of these had life-prolonging therapies and 21 (46%) had forgoing of life-sustaining treatments within 24 hours of the CT study (Fig. 1b). In 4 (2%) out of 200 CT examinations, neurosurgical procedures were performed despite a lack of new or progressive brain pathology (Fig. 1b); three of these resulted in ICP monitor placement for persistent poor neurological status and one of these resulted in...
ventriculoperitoneal shunt placement for hydrocephalus, which had been planned electively before this patient's admission. Unstable ICP was present in only 2 out of the 46 patients who had a change in management as a result of the CT findings.

Utility of Portable Head CT Scanning

It was apparent from the PRISM-III scores that portable CT scans were carried out in more severely ill patients. The raw PRISM-III score at 24 hours was 8.6 (range 1.1–45.8) in the portable group and 3.1 (range 0.51–14.9) in the fixed group ($P = 0.038$). A total of twenty-eight patients with PRISM-III risk of mortality greater than 30% underwent CT (Fig. 2); 25 (89%) of these had a portable study. On multivariate analysis by logistic regression adjusting for age, gender, and race, the adjusted risk of all cause mortality for a given PRISM-III score was increased by being in the portable group (OR, 2.26; 95% CI, 1.142–4.49; $P = 0.019$). included hypertension and bradycardia, focal weakness, hypertonia, nystagmus, or posturing; other medical conditions included hypertension, hypotension, blood pressure lability, thrombocytopenia, coagulopathy, pre-transplant evaluation, fever, or apnea. Change in med mgmt change in medical management. NS proc neurosurgical procedure. Four patients who had indeterminate findings were not included in either (a) or (b).

Fig. 1 Relationship between clinical indication, head CT findings, and impact of CT findings on patient management. Since no difference was seen between the portable and fixed groups for head CT findings or change in patient management, the results from both groups were combined in this figure. The numbers shown in the circles and squares in (a) represent the number of patients with new pathology and findings that excluded disease progression or new pathology, respectively. In (a), other neurological signs or symptoms included hypertension and bradycardia, focal weakness, hypertonia, nystagmus, or posturing; other medical conditions included hypertension, hypotension, blood pressure lability, thrombocytopenia, coagulopathy, pre-transplant evaluation, fever, or apnea. Change in med mgmt change in medical management. NS proc neurosurgical procedure. Four patients who had indeterminate findings were not included in either (a) or (b).

Fig. 2 PRISM-III risk of mortality of patients undergoing portable head CT imaging

We surmised that the intensity of interventions or therapies provided to a particular patient impacted the critical care team’s assessment of the relative feasibility of portable versus fixed CT imaging once the team had
determined that a head CT was necessary. Both the portable and fixed groups had similar rates of mechanical ventilation (79 vs. 75% in portable and fixed, respectively, \( P = 0.678 \)). However, when considering the level of PEEP used, a higher level of PEEP was associated with an increasing use of portable CT (Fig. 3a). We found a similar relationship between a higher Wernovsky score and the use of portable head CT imaging (Fig. 3b). Significant differences between groups were also found for patients receiving ECMO and iNO. Twenty-five (18%) patients in the portable group and 3 (4%) patients in the fixed group were on ECMO at the time of the first head CT study \(( P = 0.005 \)). A significant difference was also found between groups with respect to the use of iNO, with 22 (16%) patients receiving this therapy in the portable group versus one (2%) patient in the fixed group \(( P = 0.001 \)). No statistical differences were found between groups for unstable ICP or use of CVVH.

We also analyzed the subgroup of patients who underwent CT imaging while on ECMO before and after the introduction of the portable device to determine the impact of portable CT on utilization patterns. Six (4%) out of a total of 159 patients were on ECMO and received a head CT during the 22 months before the introduction of portable CT compared to 28 (22%) out of a total of 125 patients on ECMO during this study period, suggesting increased utilization of CT following the introduction of the portable device.

**Patient Dose Estimates**

The radiation dose from head CT imaging for patients in the PICU is shown in Table 1. With respect to measurement error, the radiation delivered to the patient from the portable CT scan (CTDI\(_{vol}\), 76 mGy, was within the recommended American College of Radiology guidelines of 75 mGy for adult head CT scans [18]. However, this radiation dose delivered to the patient from the portable techniques used in this study was approximately 15% greater if a fixed CT scan was performed. The estimated dose to brain tissue from the portable scanner (83 mGy) exceeded the estimated dose from the fixed scanner (72 mGy) by a similar estimate of 15% \(( P < 0.0001 \)). The effective dose from the portable machine exceeded the effective dose of the fixed CT scanner by approximately 65%. This larger discrepancy in effective dose results from longer irradiated scan lengths of the patient’s head with the portable scanner due to patient positioning difficulties at the bedside as opposed to a fixed CT scanner.

**Discussion**

Since the introduction of portable CT imaging to our hospital in 2007, clinicians have utilized this new technology for patients in the PICU with acute neurologic deterioration. The principal findings in our cohort are the

<table>
<thead>
<tr>
<th>CT group</th>
<th>CTDI(_{vol}) (mGy)</th>
<th>Effective dose (mSv)</th>
<th>*Patient dose (mGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portable</td>
<td>75.6</td>
<td>8.9 ± 3.6</td>
<td>83.4 ± 5.9</td>
</tr>
<tr>
<td>Fixed</td>
<td>66</td>
<td>5.4 ± 2</td>
<td>72 ± 5</td>
</tr>
</tbody>
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*CTDI* CT dose index, mGy milligray, mSv milliSievert

* Two-tailed *P* value < 0.0001 as determined by the independent samples *t*-test
following: any cranial CT imaging has a diagnostic yield of previously undiagnosed pathology of 40% and leads to a change in patient management in 23%; clinical practitioners use portable CT for high severity cases, and there is increased utilization among patients receiving ECMO; and the radiation dose from portable CT is within national guidelines, but the patient dose is 15% greater than that from a standard fixed CT scanner.

Head CT imaging provided a new diagnosis of brain pathology in a total of 80 (39%) patients (Fig. 1a), and the diagnostic yield did not differ between groups. Although overall reduced image quality due to increased noise and artifacts has been reported with the use of portable compared to conventional scanners, the diagnostic accuracy and reliability of portable CT is no different from that of fixed CT [6, 8]. In our study, the image quality of every head CT study analyzed was sufficient to resolve the question that prompted imaging. Two main inferences can be made from our findings. First, since the overall diagnostic yield of portable CT scanning in our series is similar to that of head CT imaging in PICU patients carried out in the radiology suite, it seems likely that CT investigation in the most critically ill patients is being used appropriately. This observation is consistent with the diagnostic yield from CT in critically ill adults, which ranges from 26 to 30% [19, 20]. Second, analysis of the ECMO subgroup supports the conclusion that patients who were receiving ECMO in the past and would have been deemed too critical to transport are now benefiting from portable CT investigation.

In regards to the clinical value of head CT imaging in critically ill patients, we found that CT investigation prompted a change in management in 23%, with no difference between the groups. This proportion is similar to the results of portable CT in adults in which 22–57% of cases have a change in therapy after imaging [2, 7, 9, 19–21]. We found that a greater proportion of portable versus fixed examinations were performed in patients requiring more intensive or complex therapies (e.g., high PEEP, high vasopressor category ≥ 5, ECMO, and iNO). This result is similar to the reports in adult neurocritical care. In a survey of physicians who ordered portable CT studies, McCunn et al. [1] found that patients who underwent portable CT imaging were those receiving ECMO (93%) and those with instability in hemodynamic (70%), respiratory (57%) and neurologic (40%) systems. In a prospective study in a neurocritical care unit, Stevens et al. [22] found that 85% of adults who had a portable head CT study had external ventricular drains or ICP monitors, 95% had arterial lines, 85% had central lines and 68% required at least one inotropic infusion. Unlike our population, larger proportions of adult patients who had portable head CT examinations had neurologic instability or had an ICP monitor in place.

Any potential benefit of a change in treatment must be weighed against the risk of conducting a CT investigation. Exposure to ionizing radiation is a major disadvantage of any CT imaging. The estimated lifetime risk of death from cancer from one head CT in the United States of America is between one in 1,000 and one in 5,000 pediatric head CT scans, with risk decreasing as age increases [13, 14]. Although the estimated radiation dose from portable CT in our study is within current national guidelines, our organ dose estimate from the portable CT machine is approximately 15% greater than the dose in patients imaged on a fixed standard scanner in the radiology suite. Even though radiation exposure limits the use of CT in children, the benefits of the diagnostic information provided and the management pathway determined as a result of the CT findings outweigh the minimal radiation exposure from a single CT study [23]. In our study, 130 (64%) patients had a single head CT study, and the diagnostic yield from a single CT scan was 40%. Therefore, an increase in organ dose of only 15% over and above a minimal radiation risk from a single CT study justifies the use of portable over fixed CT because of the risk to benefit ratio.

Our study has three main limitations. First, the retrospective study design makes an accurate assessment of the impact of CT imaging on real-time patient management difficult to assess. Therapies were often instituted empirically before the CT procedure, and documentation that clearly linked a specific clinical decision with the CT finding could not be found in some cases. Thus, no specific change in patient management could be demonstrated retrospectively for some patients. Furthermore, data on the precise interval between ordering the scan and image availability for portable and fixed CT could not be determined retrospectively. Second, data from all patients undergoing head CT imaging before the introduction of portable head CT imaging in our institution was not studied, so conclusions about whether the introduction of this device led to more or less utilization of CT or effect on patient management cannot be made. For the ECMO subgroup, however, there was an increased use of head CT imaging after the introduction of the portable machine. Third, given the retrospective nature of our study, we could not assess major complications attributable to intra-hospital transport or to the use of portable CT. However, no complications were recorded in the electronic medical records. At our institution, a CT study is performed with the following clinical team members present at the bedside: the patient’s nurse; a clinical fellow, attending critical care physician, or nurse practitioner; and a respiratory therapist. Furthermore, for every high risk patient who is transported to the radiology suite, the accompanying team carries a transport bag of equipment and emergency medications.

In conclusion, head CT imaging is a necessary investigation in pediatric neurocritical care for the diagnostic
evaluation and management of acute neurologic deterioration. Head CT imaging has a high diagnostic yield, and portable CT informs clinical decision-making for children receiving neurointensive care. Some patients are too unstable to travel to radiology, and the technology must come to their bedside. Portable head CT imaging can be carried out on the PICU in critically ill children with acceptable radiation exposure.

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Conflict of interest None.

Appendix: pCNSp members

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References


