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Estimation of effective dose and lifetime attributable risk from multiple head CT scans in ventriculoperitoneal shunted children

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Abstract

Purpose—The purpose of this review is to determine the averaged effective dose and lifetime attributable risk factor from multiple head computed tomography (CT) dose data on children with ventriculoperitoneal shunts (VPS).

Method and materials—A total of 422 paediatric head CT exams were found between October 2008 and January 2011 and retrospectively reviewed. The CT dose data was weighted with the latest IRCP 103 conversion factor to obtain the effective dose per study and the averaged effective dose was calculated. Estimates of the lifetime attributable risk were also calculated from the averaged effective dose using a conversion factor from the latest BEIR VII report.

Results—Our study found the highest effective doses in neonates and the lowest effective doses were observed in the 10–18 years age group. We estimated a 0.007% potential increase risk in neonates and 0.001% potential increased risk in teenagers over the base risk.

Conclusion—Multiple head CTs in children equates to a slight potential increase risk in lifetime attributable risk over the baseline risk for cancer, slightly higher in neonates relative to teenagers. The potential risks versus clinical benefit must be assessed.

Keywords

Effective dose; IRCP 103; Computed tomography; Ventriculoperitoneal shunted paediatric patients

1. Introduction

Radiation exposure from medical imaging has become a concern to health care professionals and the public. According to the National Council on Radiation Protection and Measurements (NCRP) report [1], a seven-fold rise in exposure from 1980s to 2006 report has mainly come from the increased utilization of computed tomography (CT) and nuclear medicine, accounting for approximately half of the increased total radiation exposure [2,3].

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Conflict of interest
None declared.

Epidemiological data from survivors of the Hiroshima atomic bomb with exposure to acute high level radiation provide findings of increased risks of cancer mortality throughout their lifespan [4]. There are no clear studies or reports on the biological effects or risk for cancer induction at low radiation levels which is the type produced by medical radiation; low linear energy transfer (LLET) ionizing radiation [5]. The paediatric population is more sensitive and susceptible to radiation effects, with the age of exposure influencing the risk of cancer induction: the younger age of radiation exposure, the higher the risk of cancer induction [2,6,7]. Children have approximately triple the lifetime cancer risk compared to adults older than 35 years [8–10]. Furthermore, children with chronic diseases are initially scanned younger, and subject to more imaging studies, therefore with increase probability of higher accumulated lifetime radiation doses. One common subgroup of children who require frequent imaging is ventriculoperitoneal (VP) shunted patients. CT is usually the standard imaging choice in most institutions and practises for this patient group. The emergency room physicians find CT a useful choice for ventricular assessment [11], as rapid imaging without sedation is preferable.

Radiation exposure and dose can be quantified using several methods; exposure can be measured as entrance surface dose, dose-area product and dose length product. While organ absorbed dose can be measured with anthropomorphic phantoms with internalized dosimeters or Monte Carlo computer simulations [12,13]. The effective dose is generally regarded as the best available dose descriptor for quantifying risks from non-uniform whole body exposure to ionizing radiation in diagnostic radiology [12,14]. It also provides an estimate comparison of relative detriment between different radiation studies. In 2008, Mettler et al. [12] performed a review of effective doses of different radiologic procedures and found the effective dose for a head CT in a neonate can be markedly higher than in an adult. While a study by Huda and Vance [13] found the effective dose for a head CT in a neonate is approximately four times higher than in an adult. Other studies have attempted to estimate the risks from exposure to head CT. Pearce et al. estimated that the risk of brain tumours could triple after exposure to the equivalent of 2–3 head CTs and the same large retrospective study estimated the risk of leukaemia and brain cancer might triple after a cumulative dose of 50 mGy and 60 mGy respectively [15]. They interpret their findings as the occurrence of one excess case of leukaemia and one excess case of brain tumour per 10,000 head CT scans. These reports of estimated risks of the study's cohort, are not transferable either geographically or between patient subgroups and do not reflect an individual's risk.

The BEIR VII report provides a reasonable alternative: the life attributable risk (LAR) of cancer incidence and mortality. LAR describes an excess of disease cases over a follow-up period with population background rate determined by the experience of unexposed individuals for each of several specific cancer sites at each age of exposure [5].

Our study's aim was to determine the average effective dose and an estimate of the lifetime attributable risk (LAR) of developing fatal cancer in VP shunted children who were repeatedly imaged at our institute.

Additionally, we discuss an alternative non-ionizing imaging method using a fast MR imaging technique that has the potential to minimize the radiation burden in patients with chronic conditions.

2. Materials and methods

This single institutional retrospective study was IRB approved and HIPAA compliant. The Radiology Information System (RIS) and Picture Archiving and Communication System (PACS) at our medical centre were used to identify all head CTs with a keyword search function. The search was refined and included all head CT examinations for paediatric VP shunted patients from October 2008 (the date of CT dose introduction into the imaging folders in our PACS System) to March 2012. In our study, patients older than 18 years were considered adults and all other clinical indications or CT studies without a dose report were excluded.

2.1. CT scanners

The following CT scanners are utilized in our hospital: Philips Brilliance 64 slice, Philips Brilliance 16 slice, Philips iCT 256 slice and Neurologica Ceretom portable 6 slice.

The imaging studies were reviewed on a Phillips PACS workstation and the dose report of each CT head examination was reviewed. The tube peak voltage (kVp), tube-current-time product (mAs), dose length product (DLP) and volume computed tomography dose index (CTDI_{vol}) was recorded.

2.2. Effective dose calculation method

Organ doses can be characterized both in terms of equivalent doses and weighted equivalent doses. The equivalent dose E to a particular organ corresponds to the equivalent dose of a hypothetical scan in which each organ received the same dose as the particular organ in the original scan. Weighted equivalent dose corresponds to the contribution of E to a particular organ, and is calculated by multiplying E by a tissue-weighting factor.

The tissue-weighted coefficients (Table 1) used were the most up to date published by International Commission on Radiological Protection 103 (ICRP) in 2007 [16,17]. The ICRP 103 provides tissue-weighting factors as a function according to tube voltage (kVp); scan region and age, reflecting the relative radiation sensitivity of each body tissue determined from population averages.

The effective dose was calculated using an organ dose method with tissue-weighted coefficients and scanner-derived dose-length product (DLP).

$$E = E_{\text{DLP}} \cdot \text{DLP}.$$

E_{DLP} is a conversion factor, depending on the region of the body and relating DLP to the equivalent dose E . Our study patients were grouped into the same age groups that corresponds to ICRP phantoms: (a) new-born, (b) one year old, (c) younger than or equal to

5 years, (d) older than 5 years and younger than 10 years, (e) older than 10 years and younger than 18 years.

Table 1a–e show the conversion factor; E_{DLP} derived from DLP to effective dose E as a function of voltage, region, and age. These conversion factors are taken from the most recent ICRP Publication 103 recommendations [17] and were used to calculate the effective dose.

2.3. Assumptions and risk calculation

Cancer mortality risk varies considerably from site to site and gender specific rates of cancer incidence. Factors related to gender when evaluating risks for CT head examinations are negligible as estimated brain tumour risks are not likely to vary with gender and thus it was not factored into our calculations. The linear no-threshold model for cancer risk is widely accepted and was used to estimate the lifetime attributable risk (LAR) of cancer incidence and mortality in our study [18,19]. The age of the first head CT study was assumed as the patient's age at the time of their first CT head exam at our institute. There is currently no study available to provide a weighting factor or estimate on the additional radiation that patients may be exposed to due to either patients shopping to cut cost in the United States or due to an emergent episode. The estimate for the LAR was performed multiplying the averaged effective dose that each patient received with the most recent standardized BEIR VII conversion factor of 0.0001/mSv [5].

2.4. Statistical analysis

The data was tabulated in Microsoft Excel 2007 (Microsoft Inc., Redmond, WA, USA) and descriptive statistics was performed with generation of Whisker-box-plots with Origin (OriginLab, Northampton, MA, USA) for the averaged effective dose.

3. Results

3.1. Patient population

A net total of 138 patients (63 males and 75 females) who underwent 422 CT head examinations were included in our study. Three patients of a total of 141 patients were excluded due to lack of dose report data. The youngest patient in our study was less than 1 month old and the oldest at initial presentation was 18 years 0 months. The mean age of the first head CT exam in our institute was 8.96 years, with a median of 8.33 years and mode of 14.83 years. The patients were grouped according to similar age groups that are available for phantoms. The distribution of our study patients is displayed in Table 2.

The total number of head CTs including repeat exams were 422 and 410 of these CT head exams were not repeated. The repeat CT head studies were performed in a total of 10 children ($0.08\% = 10/138$) and they had a total of 12 repeat exams. The commonest reason for a repeat exam was motion artefacts and poor diagnostic quality on the initial study. The number of CT head exams performed per patient ranged from 1 to 37 scans with a mean of 3 scans. The maximum number of scans that was repeated in one episode was 17.

3.2. Scan parameters and mean effective dose

Scan parameters of our study include time current time product (mAs), tube voltage (kVp), dose length product, CT dose index CTDI_{vol} (mGy) and dose length product (mGycm) are displayed in Table 3.

CTDI_{vol} in our study was 36.8 ± 6.31 mGy and the mean DLP ($\text{DLP} = \text{CTDI}_{\text{vol}} \times \text{scan length}$) was 717 ± 92.6 mGycm. Additional details of the data analysis are displayed in Table 3.

The mean effective dose E mSv was calculated for each CT head scan performed on each patient in our institution. The mean effective dose was obtained by calculating the effective dose per scan and the effective doses per scan were averaged to obtain the averaged effective dose per patient. The highest effective doses and averaged effective doses were observed in patients aged 0–1 years and the lowest effective doses were in the 10–18 years group.

The child who received the highest effective dose of 7.61 mSv as well as the highest average effective dose of 7.38 mSv was a neonate less than a month old. This child was only scanned twice and due to the function of their age, the calculated effective dose was the highest. The lowest effective dose of 0.63 mSv and an average effective dose of 1.06 mSv were observed in a 13 years and 1 month old patient. The distribution of the averaged effective doses in each age group are displayed in Fig. 1 as Whisker box plots with mean, median, 25-percentiles/75-percentiles on the boxes and 5/95-percentiles on the whiskers.

3.3. Risk estimate

The calculated estimated lifetime attributable risk (LAR) was 0.00074, which equates to a potential increased risk of 0.007% in a neonate over the base rate risk. This means that there will be potentially an excess of 74 cancers observed in a population of 100,000.

The calculated estimated lowest LAR was 0.000105707, which equates to a 0.001% potential increase risk in a teenager over the base rate risk. This means that there will be the potential for one additional cancer in a paediatric patient population of 100,000.

4. Discussion

The goal of our study was to determine the risk from radiation exposure resultant from multiple head CT imaging in children with VP shunts. Over the past decades, there has been a rise in the use of CT imaging [20], raising concerns of the effects of ionizing radiation in children [21]. Increased incidence of thyroid cancer by 62-fold has been found in child survivors of natural radiation disasters when the nuclear plant in Chernobyl in 1986 exploded. The thyroid cancers that developed in children in the Chernobyl study had a shorter latency, more aggressive histology and earlier age of cancer development compared with children who received neck irradiation [22].

Unlike high dose acute radiation exposure from natural disasters or nuclear bombing, there is no consensus or published studies on the effects of chronic exposure to low levels of low

linear energy transfer (LET) radiation, the type from medical radiation. The data on estimates of radiation risks from chronic exposure to low levels of LET radiation have been derived from mortality and cancer statistics following the survivors of atomic bombing in Hiroshima, Japan known as the Life Span Study [23]. The Life Span Study is the best available data from the largest cohort with the longest follow-up data of survivors from high dose exposure. While there are no comparable epidemiological or ethical studies available on the effects of radiation risk following exposure to LET due to a long latency period between exposure and event. What we can calculate is the effective dose; which takes into account the relative radiosensitivity of organs by using a tissue-weighting factor from the most recent ICRP Publication 60 [16]. ICRP 60 introduced a weighting factor for brain tissue to the list of identifiable radiosensitive tissue compared with prior ICRP reports.

One of the main findings in our study is an increase in effective radiation doses in the neonates with the lowest effective radiation doses in the teens and late teens. Effective doses in older teenagers are comparable to young adults. These findings are similar to other studies [13,24] where effective doses were higher in children compared to adults.

Our effective doses are in agreement to a study by Huda et al. where they analyzed CT head dosimetry using paediatric and adult phantoms [25] and another study by Miglioretti et al. [26], who investigated effective doses from CT according to age and anatomic region. These results also indicate that our head CT protocols could be further improved for paediatric patients.

The FDA has published recommendations on reducing radiation doses in the paediatric population without significant compromise in image quality using the ALARA principle (as low as reasonably achievable) [27]. There are several factors, which influence the absorbed radiation from CT, some are inherent and uncontrollable while others are potentially controllable factors e.g. mAs and kVp [28]. Optimizing these controllable parameters can significantly alter the radiation dose without compromising image quality. It has been shown to be possible in a few studies whereby the investigators successfully implemented radiation dose reduction strategy for their Neuro-CT protocols, obtained lower doses for their paediatric brain CT compared to adult brain CTs [29,30].

In addition to optimizing scanner protocols, other strategies include reducing the number of repeat exams predominantly due to motion artefact, which was the main reason in the majority of our repeated studies. Another tactic is to utilize magnetic resonance imaging (MRI). MRI is a non-ionizing imaging technique that offers multi-angle, multi-planar capabilities and could potentially replace head CT imaging. Fast brain MRI techniques [30] have improved in the last decade and have various clinical applications especially in CNS imaging. There are several fast MRI sequences [31–33] mostly based on single-shot fast spin echo T₂-weighted sequences [30] and can be acquired without sedation which is especially suited for paediatric patients. Fast brain MRI has been investigated and can be used to replace head CT for evaluation of ventricular size [34]. One main advantage of fast brain MR imaging is that there is no need for sedation or its associated sedation risks [35–38]. There are drawbacks of MRI but these can potentially be reduced. One drawback is its reduced specificity in delineation of shunt catheter tips compared to CT imaging. However,

the conspicuity of intracranial catheters can be improved if a gradient recalled echo sequence [32] is added to the protocol. Another drawback is that this MR technique is limited in assessment of brain parenchyma and any lesions smaller than 5 mm [39].

BEIR VII [5] primary objective was to develop the best possible risk estimate for exposure to low-dose LET and have advocated the use of the Linear No Threshold (LNT) model as a practical model when estimating risks in radiation protection matters. The basis for the “linear no-threshold model” is that the estimated risk is thought to be linear at lower doses and even the smallest dose has the potential to result in a small increase in risks to humans. This is a widely but not universally accepted model [18,19], and we too have applied LNT model in our study. Estimating the fatal cancer risk ideally uses the Lifetime Attributable Risk (LAR) as a primary risk measure [5] and the LAR represents the estimated cancer above the base rate. We estimated a 0.007% potential increase risk in neonates and 0.001% potential increased risk in teenagers over the base rate. There is no data precisely defining the base rate risk specific to children with shunted hydrocephalus but we do know that subtypes of cancer vary by age with acute lymphocytic leukaemia (26%) and brain and CNS tumour (21%) being the top 2 commonest tumour in children before age 14 years. These two cancers are the main concerns of potential radiation risk related to multiple head CTs. However our estimated potential increase risk in neonates and teenagers is tiny relative to the background risk (0.24%) in a child born in the US of developing cancer before age 15 years or equivalent to an average of 1 new cancer in 408 children diagnosed before age 15 years [40].

We recognize and accept that our data is likely an underestimation of radiation exposure when calculating the LAR, based on the assumption that the first age of exposure to CT is the age of the patient in our study and that there have been no other CT head studies performed at other facilities or other CT exams at our institution. This could be true in neonates but unlikely in the older children. In our very large metropolitan area nearing a population of 10 million, there are 7 major academic medical centres and teaching hospital, 6 children’s hospitals (4 free-standing), over fifty community hospitals, and innumerable outpatient imaging centres. Additionally, there is a substantial variability in CT scan doses between facilities. For these reasons, we do not believe we can accurately estimate the number of CT scans outside of our system and thus cannot provide even a best guestimate of additional radiation exposure and dose for our study population.

Another potential factor for underestimating the LAR in our study is that dose reports were not included in the PACS study folders at our institution before 2008 and examinations before this date were not included in this study. Even allowing for these factors, our CT head doses are well below 200 mGy or 0.1 mGy/min, the worrisome dose level set by United Nations Scientific Committee on the effects of atomic radiation (UNSCEAR) [5,41] which has been based on review of radiobiological and epidemiological data. The BEIR report defines low dose as a dose less than 100 mSv, equivalent to 40 times the average yearly background exposure [5] or less than 0.1 mGy/min over months or a lifetime. Our estimated LAR still falls below theses levels. Data from a large epidemiology study found the relative risk of brain tumours receiving 50–74 mGy was 2.82 and relative risk of

leukaemia who receive at least 30 mGy was 3.18 from radiation exposure from CT scans in childhood [15].

As inherent in retrospective studies, there is a patient selection bias and we also had a small sample size. Obviously a larger study group would provide a stronger statistical power. One large study found a higher LAR of 0.7% [42] of total expected baseline cancer incidence, and the study by Miglioretti et al. [26], estimated the projected lifetime attributable risk of leukaemia was 1.9 cases per 10,000 head scans for children younger than 5 years of age. Regardless, these findings and our findings equate to an overall tiny increase risk over the baseline cancer incidence. This potential risk has to be balanced between the risks from an emergent event. Implementing and replacing head CT with the non-ionizing fast MRI technique to evaluate ventricular size in children with VP shunts would be beneficial.

Summary

We have attempted to determine the risk from low dose radiation exposure from head CT imaging but some controversies exist about the potential carcinogenic effects of low dose radiation exposure. Risk estimates are population based and cannot be transferred between populations due to environmental differences as well as the applicability of transferring mortality and cancer statistics between different populations. The risk estimate is not meant to provide an individual patient-specific risk. This is a question that parents often ask radiologists or other healthcare professionals.

In our study, we have attempted to estimate the degree of risk from our cohort of paediatric patients with VP shunts who are repeatedly imaged with head CTs. Our results reflect the best guestimate possible in this patient population.

Multiple head CTs in children likely equates to a minimal potential increase risk in lifetime attributable risk relative to the baseline risk for cancer, higher in neonates relative to teenagers. The probability of inducing an abnormality is likely less than the natural occurrence and the marginal potential increase in risk is outweighed by the benefits of diagnostic potential. Additionally, the value for the role of non-ionizing imaging technique is strengthened especially in patients who require repeated imaging over their lifetime and this alternative could be considered and implemented more universally.

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Fig. 1. Whisker-box-plots displays the mean, median, 25-percentiles/75-percentiles on the boxes and 5/95-percentiles on the whiskers of the average effective dose per age group.

Table 1

a–e show the conversion factor; EDLP derived from DLP to effective dose E as a function of voltage, region, and age.

(a)	
New-born phantom	Head
Tube voltage [kV]	E_{DLP} [mSv]
80	0.0094
100	0.0088
120	0.0085
140	0.0082
Mean	0.0087
(b)	
1 Year old Phantom	Head
Tube voltage [kV]	E_{DLP} [mSv]
80	0.0056
100	0.0054
120	0.0053
140	0.0052
Mean	0.0054
(c)	
5 Years old phantom	Head
Tube voltage [kV]	E_{DLP} [mSv]
80	0.0035
100	0.0035
120	0.0035
140	0.0035
Mean	0.0035
(d)	
10 Years old phantom	Head
Tube voltage [kV]	E_{DLP} [mSv]
80	0.0026
100	0.0027
120	0.0027
140	0.0027
Mean	0.0027
(e)	
Adult phantom	Head
Tube voltage [kV]	E_{DLP} [mSv]
80	0.0018

(a)	
New-born phantom	Head
Tube voltage [kV]	E_{DLP} [mSv]
100	0.0019
120	0.0019
140	0.0019
Mean	0.0019

Table 2

Demographics of our study group.

Age	Number of patients
New-born to 1 year	14
1–5 years	28
5–10 years	33
10–18 years	63

Table 3

Statistical analysis of tube voltage (kVp), tube-current-time product (mAs), dose length product (DLP) and computed tomography dose index (CTDI_{vol}) in 138 ventriculoperitoneal shunted paediatric patients. A total of 422 of the studies were performed (including multiple repeat scans). 410 of the studies were performed without repeats.

	CTDI _{vol} [mGy]	mAs	kVp	DLP [mGycm]
Mean	36.8	386.7	106.4	717.2
Mode	38.8	480	100	745.1
Median	38.8	400	100	723
Standard deviation	6.31	96.7	9.45	92.6