Doses from CT examinations to children suffering from hydrocephalus

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Abstract. Children with shunt treated hydrocephalus are likely to receive high accumulated doses due to frequently head CT examinations throughout their lives. Follow-up CT examinations of 67 children were retrospectively studied, resulting in an investigation of 672 individual CT examinations. Calculation of effective doses was based on applied scanner parameters and tabulated conversion factors for an 8 week old baby and a 7 year old child. Lens doses and brain doses were estimated by use of tabulated CTDI values measured in the centre and periphery of a standard head phantom (16 cm in diameter). Mean effective dose, eye lens dose and brain dose to children were 1.2 mSv, 52 mGy and 33 mGy, respectively. Doses to babies were generally higher than those to children. Average CT examinations per year during childhood were slightly over one. Increased lifetime cancer mortality is expected for these children due to numerous CT examinations during babyhood. Accumulated lens doses were less than the threshold dose for lenticular opacity, while the accumulated brain dose exceeded the assumed threshold dose for cognitive reduction in adulthood for almost all patients. No systematic use of paediatric CT protocols was observed among these patients, addressing the need for optimization of CT protocols used on children with shunt treated hydrocephalus.

1. Introduction

Hydrocephalus is a condition in which the primary characteristic is excessive accumulation of cerebrospinal fluid (CSF) in the brain, often resulting in enlarged ventricles (FIG. 1). The condition is usually treated by surgical placement of a shunt system, which maintains the flow of the CSF (FIG. 2a). To verify the functionality of the shunt system, it has been common practice to follow the patients with frequent cerebral CT examinations throughout their lives (FIG. 2b). The incidence of hydrocephalus is approximately 1-2 out of 1000 and is most common in children [1]. It is generally recognized that patient doses from CT examinations are high in comparison with other types of radiographic examinations [2]. Children suffering from hydrocephalus are therefore likely to receive high accumulated doses, especially to their eye lenses and brain. Exposure of the eye lens may induce lenticular opacity if the dose received exceeds the threshold dose 0.5-2 mGy [3, 4]. New research also indicates that exposure of the brain during early childhood to more than 100 mGy may result in reduced cognitive function in adulthood [5]. Children are also exposed to a greater risk of developing stochastic late effects like cancer due to their increased radiosensitivity compared to adults [6]. Considering the numerous CT examinations children with hydrocephalus may undergo, it is important to optimize the examinations according to clinical questions asked, especially in newborns, to minimize the doses. The aim of the present work was to study a group of hydrocephalus patients retrospectively, in order to evaluate the doses involved. The use of optimized CT protocols, especially for use on paediatric patients, was also investigated.
2. Material and methods

2.1. Patient material and CT examinations

This study was based on 67 children with shunt treated hydrocephalus born from 1983 to 1995. All CT examinations carried out on these children during their lives, from birth to the year 2002, were studied. In total, this involved investigation of 672 individual CT examinations. The CT examinations were mainly performed at Haukeland University Hospital (HUH); 4% of the examinations were carried out at other hospitals. The different CT scanners used to perform the follow-up examinations in this study are shown in Table I, time periods of which the scanners were in use and total number of performed examinations is also included. The applied scan parameters were retrieved from the X-ray archive and registered for all CT examinations together with the patient’s age and date of examination.
Table I. The different CT scanners used to perform the examinations in this study, their time period in use and total number of performed examinations.

<table>
<thead>
<tr>
<th>CT scanner</th>
<th>Time period in use [years]</th>
<th>No. of examinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE 9000</td>
<td>1987-1994</td>
<td>19</td>
</tr>
<tr>
<td>GE 9800</td>
<td>1984-1995</td>
<td>241</td>
</tr>
<tr>
<td>GE Sytec</td>
<td>1995-2001</td>
<td>34</td>
</tr>
<tr>
<td>GE HiSpeed Advantage</td>
<td>1995-2001</td>
<td>227</td>
</tr>
<tr>
<td>GE Light Speed Plus</td>
<td>2001</td>
<td>3</td>
</tr>
<tr>
<td>GE Prospeed SX Power</td>
<td>1997</td>
<td>1</td>
</tr>
<tr>
<td>Siemens Somatom DR</td>
<td>1994</td>
<td>1</td>
</tr>
<tr>
<td>Siemens Somatom Plus 4</td>
<td>1998-1999</td>
<td>2</td>
</tr>
<tr>
<td>Philips LX</td>
<td>1991-2001</td>
<td>142</td>
</tr>
<tr>
<td>Toshiba Xvision</td>
<td>1996-1997</td>
<td>2</td>
</tr>
</tbody>
</table>

2.2. Calculation of effective dose

The effective dose was estimated by using the method described by Nagel et al. [7] and calculated by the following equation:

\[ E = n \cdot CTDI_{air} \times Q \times n \times N \times h \times f_{mean} \times k_{CT} \times \left( \frac{U}{U_{ref}} \right)^{2.5} \]  

where

\( n \cdot CTDI_{air} \) normalized computed tomographic dose index measured free-in-air at the axis of rotation;
\( Q \) tube current-time product (mAs);
\( n \) total number of sections;
\( N \) number of sections per rotation (= 1 for single slice scanners);
\( h \) section thickness;
\( f_{mean} \) mean conversion factor from \( n \cdot CTDI_{air} \) to effective dose;
\( k_{CT} \) scanner-specific correction factor;
\( U_{ref} \) reference tube voltage for establishment of \( f_{mean} \);
\( U \) applied tube voltage.

Tabulated values of \( n \cdot CTDI_{air} \) and \( k_{CT} \) were used in the calculation of effective dose [7, 8]. Mean conversion factors \( f_{mean} \), based on Monte Carlo simulations in phantoms, were only available for an 8 week old baby (\( f_{mean, baby} \)) and a 7 year old child (\( f_{mean, child} \)) [9]. Based on typical body length for children, \( f_{mean, baby} \) was applied to newborns and patients up to an age of 6 months, while \( f_{mean, child} \) was applied to all patients older than 6 months. These two patient groups are referred to as babies (when \( f_{mean, baby} \) were used) and children (when \( f_{mean, child} \) were used) for simplicity in the rest of this text.

2.3. Estimation of eye lens dose and brain dose

The computed tomographic dose index (CTDI) measured in the periphery (CTDI\(_{p}\)) 1 cm below the surface of a standard CTDI phantom (16 cm in diameter) was used as an estimate of the eye lens dose when the eye lenses were included in the scan field. No estimation of the lens dose was performed for those patients whose eye lenses were excluded from scan field. The volume CTDI value (CTDI\(_{vol}\)) was used as an estimate of the brain dose. CTDI\(_{vol}\) is given by:
CTDIB\textsubscript{vol} = \frac{CTDIB\textsubscript{w}}{p} = \left( \frac{1}{3} CTDIB\textsubscript{c} + \frac{2}{3} CTDIB\textsubscript{p} \right) \times \frac{1}{p}

where

CTDIB\textsubscript{w} \quad \text{weighted CTDI value;}

p \quad \text{pitch factor;}

CTDIB\textsubscript{c} \quad \text{CTDI value measured in the centre of a standard head phantom (16 cm in diameter).}

Tabulated values of CTDIB\textsubscript{p} and CTDIB\textsubscript{c} were used in the estimations of the eye lens dose and brain dose [8]. By using the CTDI values measured in the standard CTDI head phantom simulating an adult head (16 cm in diameter) the doses to babies and small children will be underestimated, due to their smaller head diameter. In order to estimate the magnitude of this underestimation, a smaller phantom simulating a baby head (10 cm in diameter) was fabricated (FIG. 3a). CTDI measurements were made in the centre (CTDIB\textsubscript{c}), in the periphery 1 cm below the surface (CTDIB\textsubscript{p}) and on the surface (CTDIB\textsubscript{s}) for both phantoms (FIG. 3b). Preliminary results indicate that both CTDIB\textsubscript{c} and CTDIB\textsubscript{p} are about 20% higher in the baby phantom compared to the adult phantom. To compensate for this underestimation the tabulated CTDI values were increased by 20% for all newborns and patients up to 6 months of age, before they were used to estimate doses to the eye lens and brain. The 6 months limit was based on the average head diameter on babies. In both phantoms, CTDIB\textsubscript{c} and CTDIB\textsubscript{p} measurements were almost identical, indicating that use of CTDIB\textsubscript{p} is a good estimate of the lens dose.

2.4. Accumulated doses

Accumulated doses (effective, lens and brain) received through childhood were calculated for those children who had been routinely followed up by CT examinations for a period of 10 years, starting at birth. Independently from this, accumulated doses during babyhood (from birth to 18 months) were also calculated for those children who had performed more than 5 CT examinations during this period. The patient material allowed for calculation of accumulated doses through childhood and babyhood for 13 and 10 patients, respectively.
2.5. Use of paediatric CT protocols

To investigate if paediatric CT protocols were used for babies in the regular follow-up examinations of children with shunt treated hydrocephalus, a comparison of the applied mAs were done within each of the three most frequently used scanner models. A reduction in applied mAs for examinations performed on babies compared to children for the same CT scanner model indicates the use of a paediatric CT protocol.

3. Results

Table II summarizes the mean effective dose, lens dose and brain dose per CT examination for babies and children with shunt treated hydrocephalus. The total number of CT examinations carried out and the number of examinations which exposed the eye lens to the primary beam are also included in the table. Mean doses were generally higher for babies than children, mainly due to their smaller body length and head diameter. The largest difference was however observed for the effective dose, which was approximately a factor 2.6 higher for babies than for children. When regarding the lens exposure, 27% of all the CT examinations performed on babies included their eye lenses in the scan area, while the corresponding amount among the adults was 10%. The mean lens dose per examination to babies and children was 60 mGy and 52 mGy, respectively, when lenses were included in the scan area. The brain dose was approximately 45% higher for babies than for children. Large variations were observed from examination to examination within all three dose types.

Table II. Mean effective dose, lens dose and brain dose per CT examination to babies and children suffering from hydrocephalus. The total number of CT examinations performed together with the number of examinations which exposed the eye lens to the primary beam is also given. SD is the standard deviation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Babies (≤ 6 months)</th>
<th>Children (&gt; 6 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective dose [mSv]</td>
<td>3.2 ± 1.4 (0.5-6.4)</td>
<td>1.2 ± 0.8 (0.1-3.9)</td>
</tr>
<tr>
<td>Lens dose [mGy]</td>
<td>60 ± 21 (29-103)</td>
<td>52 ± 22 (12-129)</td>
</tr>
<tr>
<td>Brain dose [mGy]</td>
<td>48 ± 19 (6-100)</td>
<td>33 ± 21 (4-92)</td>
</tr>
<tr>
<td>No. of CT examinations</td>
<td>62</td>
<td>610</td>
</tr>
<tr>
<td>No. of lens exposures</td>
<td>17</td>
<td>63</td>
</tr>
</tbody>
</table>

Thirteen patients had been routinely followed up by CT examinations for a period of 10 years, starting at birth. The accumulated effective dose, lens dose and brain dose to these patients are shown in Figure 4. The mean (min-max) number of CT examinations during this follow-up time was 13 (9-19), indicating slightly more than one examination per year. The mean accumulated effective dose, lens dose and brain dose were 19 mSv, 132 mGy and 503 mGy, respectively. Ten patients underwent five or more CT examinations during babyhood (up to 18 months). The mean number of CT examinations during babyhood for these patients was seven, resulting in a mean accumulated effective dose and brain dose of 13 mSv and 300 mGy, respectively. The majority of these patients had their eye lenses exposed for the primary field once during the examinations, giving a typical lens dose of 50-60 mGy. One of the patients had performed 12 CT examinations during babyhood, which resulted in an accumulated brain dose of 500 mGy. The accumulated lens dose for this patient, whose eye lenses were exposed to the primary field in 6 of the 12 examinations, was 290 mGy. These results show that children suffering from hydrocephalus may receive accumulated doses where lenticular opacity and reduced cognitive function may occur.
FIG. 4. Accumulated doses from CT examinations to 13 children during childhood (newborn to 10 years old). a) Effective dose. b) Lens dose. c) Brain dose. Number of controls for each child is quoted above each bar. In the case of lens dose the number of examinations which exposed the lens for the primary beam together with the total number of controls (in brackets) is quoted above each bar.

Table III summarize the mean applied current-time product (mAs) together with the number of CT examinations and effective dose per examination for babies and children for the three most frequently used CT scanners. No significant difference between the applied mAs for CT examinations performed on babies and children was observed within the two GE scanners. However, a reduction of the applied mAs for examinations on babies may be indicated for the Philips scanner. Table III also shows that effective doses received from the three different CT scanners may vary by a factor of 3.
Table III. Applied current-time product together with the number of CT examinations and effective dose per examination for babies and children for the three most frequently used CT scanners at HUH. SD is the standard deviation

| Scanner          | Babies | | Children | |
|------------------|--------|------------------|---------|
|                  | Mean ± SD (min-max) | Mean ± SD (min-max) |
| GE 9800          |        |                  |
| No. of CT exams  | 37     | 191              |
| Current-time prod [mAs] | 310 ± 49 (22-340) | 338 ± 50 (140-510) |
| Effective dose [mSv] | 3.3 ± 1.2 (0.5-6.4) | 1.2 ± 0.5 (0.3-3.2) |
| GE HiSpeed Advantage |      |                  |
| No. of CT exams  | 6      | 221              |
| Current-time prod [mAs] | 223 ± 116 (90-340) | 205 ± 82 (102-340) |
| Effective dose [mSv] | 2.1 ± 1.5 (0.7-4.3) | 0.6 ± 0.5 (0.1-2.5) |
| Philips LX        |        |                  |
| No. of CT exams  | 12     | 130              |
| Current-time prod [mAs] | 238 ± 114 (238-580) | 426 ± 55 (238-580) |
| Effective dose [mSv] | 3.3 ± 1.7 (0.9-6.4) | 1.8 ± 0.7 (0.4-3.9) |

4. Discussion and conclusion

4.1. Methods for dose calculations and estimations

Few established methods for calculations of effective dose to paediatric patients from CT examinations are available. The method described by Nagel et al. [7], used in this study, is based on tabulated mean conversion factors for head CT examinations for an 8 week old baby and a 7 year old child [9]. Only two conversion factors were therefore available for calculating the effective dose for all the patients represented in this study. Chapple et al. showed that the effective dose from head examinations on children decreased exponentially with increasing body length and flattens off at body lengths of about 110 cm [10]. This huge difference in effective dose due to body length is explained by the differences in distance between the radiosensitive organs (in the trunk) and the scan area and hence the amount of scattered radiation reaching these organs. The use of one single conversion factor ($f_{\text{mean, baby}}$) for all the children between newborn and 6 months will therefore underestimate the doses to newborns and overestimate the doses to children of 6 month old. The use of $f_{\text{mean, child}}$ for all the remaining patients above 6 months will also lead to under- and overestimations, but not to the same extent due to the exponential relationship between effective dose and patient length. A mean conversion factor for adults ($f_{\text{mean, adult}}$) was also available for use in calculating the effective dose [9]. This conversion factor was not applied to any of the patients in this study, since no CT examinations were carried out on patients older than 16 year old. The use of tabulated values for $n\text{CTDI}_{\text{air}}$ instead of measured values introduce an uncertainty of about 20%, while the use of a scanner-specific correction factor are related to an uncertainty of ±10%. In addition, the influence of patient thickness is not taken into account in the calculation of effective dose in this study. Typical effective doses from head CT examinations of adults, children and babies are 1-2 mSv, 3 mSv and 6-8 mSv, respectively [11-13], indicating that effective doses to babies are heavily underestimated in this study. Another aspect that has to be considered in the calculation of effective dose is the uncertainty of tissue weighting factors for newborns and small children, since the ICRP weighting factors used to derive $f_{\text{mean, baby}}$ and $f_{\text{mean, child}}$ are based on adults [3].

The use of CTDI values (CTDI$_p$ and CTDI$_c$) to estimate organ doses gives a good indication of the dose if the organ is totally included in the scan area and located near the measuring position (centre or surface) [7]. This assumption is assumed to be valid for the eye lenses when included in the scan area. Typical eye lens doses, when included in the scan are, are shown to be 50-70 mGy for adults [13, 14], indicating that CTDI$_p$ gave a reasonable estimate for the lens dose of children. Eye lens doses were not estimated for those examinations which excluded the eye lens from the scan area. Even though the
lens is not exposed to the primary beam they will receive doses due to scattered radiation from adjacent radiated areas. However, eye lens doses are expected to be much lower when excluded than included in the scan area. The received eye lens dose, when excluded from the scan area, is shown to be approximately 5-7 mSv or less [13, 14]. The brain is not located entirely in the centre of the head and is therefore best represented by the weighted CTDI value corrected for the applied pitch factor (CTDIvol). The uncertainties in the brain dose estimations are believed to be larger than for the lens dose, since the brain was not fully included in the scan area in all the examinations. Typical brain doses to children are showed to be approximately 30 mGy [6], indicating that also CTDIvol gave a reasonable estimate for the brain dose to children. However, the lens dose and brain dose to newborns are believed to be heavily underestimated, since the relationship between CTDI value and phantom diameter also are shown to be exponential, increasing with decreasing diameter [11, 12, 15, 16]. The obtained 20% lower CTDI values in the 10 cm in diameter phantom compared to the 16 cm in diameter phantom are in good agreement with the literature [15]. The use of tabulated CTDI values instead of measured ones, introduce an uncertainty of about ± 20% in the estimations of lens dose and brain dose.

4.2. Doses and risks

It is generally accepted that use of diagnostic X-rays involves a risk for radiation-induced fatal cancers. The combination of higher doses to children for a given CT examination and the much larger lifetime risks per unit dose that applies to children, results in lifetime cancer mortality attributable to CT examinations that is significantly higher in children than in adults. When considering lifetime cancer mortality attributable to head CT examinations on babies (one year old) an estimated excess risk of 0.07% was found [6]. Another study showed a significant increase in intracranial tumours for babies with skin haemangioma who were treated by ionising radiation before 5 months of age, indicating an excess relative risk of 4.5/Gy [17]. Some children with shunt treated hydrocephalus represented in this study performed more than five head CT examination during their babyhood, some carried out before the age of 5 months. Based on these results justification of CT examinations is questionable, since examination by ultrasound may give the same information on babies [18].

Radiation induced lenticular opacity is well known from the Japanese A-bomb survivals [3]. The same relationship was also observed in a study dealing with radiotherapy of skin haemangioma on children, indicating an excess risk of 50% for doses grater than 1 Gy together with an increased risk for babies younger than four months [4]. The indicated threshold doses for lenticular opacity when received in a single exposure and accumulated throughout highly fractionated exposures are 0.5-2 Gy and 5 Gy, respectively [3]. Both the mean and accumulated lens doses obtained in this study were substantially less then these threshold doses. However, the effects of repeatable exposures of the eye lens during lifetime are not so well established. The International Commission on Radiological Protection (ICPR) indicates a much lower threshold annual lens dose of 100 mGy/year if the dose is received yearly in highly fractionated of protracted exposures for many years. In the case of children with shunt treated hydrocephalus, who undergo head CT examinations throughout their lives, this lower threshold dose may need to be considered in the evaluation of risks for lenticular opacity. Based on the average number of CT examinations during childhood and the mean eye lens dose per examination, a theoretical eye lens dose of approximately 65 mGy/year was obtained if all examinations included the eye lens in the scan area. However, it is questionable if almost yearly CT examinations can be considered as highly fractionated. Based on the high theoretical accumulated dose to the eye lens it is extremely important to avoid exposure of the eye lens for this patient group. By tilting the gantry, the eye lens can easily be excluded from direct exposure without loosing important diagnostic information. Although a tilted gantry was part of the protocols used, 12% of the performed examinations included the children’s eye lens in the scan area reflecting a need for optimisation of the examinations.

For long, the brain has been considered a comparatively radioresistant organ. However, newer research shows that low doses of ionizing radiation to the brain in babyhood (up to 18 months) may influence the cognitive abilities in adulthood, indicating a threshold dose of about 100 mGy [5]. Most children with shunt treated hydrocephalus in this study received a brain dose exceeding this threshold
dose during their babyhood, while the mean accumulated dose received through childhood was 500 mGy. Brain doses approaching 100 mGy from one single CT examination on both babies and children were observed. Since hydrocephalus alone poses a risk to reduced cognitive development if left untreated, together with the excess risk due to frequent CT examinations, an optimization of the cerebral CT examinations in this patient group is extremely important to reduce the brain dose.

4.3. Optimization of CT examinations

The large variation in doses observed between examinations addresses a need for optimization of the follow-up CT examinations used in children with shunt-treated hydrocephalus at HUH. Optimization of CT examinations requires selection of scan parameters which minimize the radiation dose to the patients without significantly impacting upon the diagnostic accuracy of the examination. The best way to start an optimization procedure is by finding the appropriate mAs, since the patient dose are proportional with the applied mAs. Two main factors must be considered in selection of the appropriate mAs value; CT scanner in use and actual size of the patient being examined. Different CT scanners have different architecture and detector efficiency, resulting in different patient doses for identical applied scan parameters. The variation between different scanner models in applied mAs to give the same patient dose may therefore vary by a factor of two to three. New CT scanners usually maintain image quality at a much lower dose than older ones, resulting in unnecessary high dose if protocols designed for old scanner models are adapted to new ones. Calibration of each individual CT scanners to establish the relationship between patient dose (mAs) and image noise is therefore necessary. Further, X-ray attenuation decreases with decreasing patient size, resulting in unnecessary high patient doses if the same mAs value are applied independent of patient size. For head CT examinations of newborns and small children the applied mAs should therefore be reduced to compensate for the increased patient dose due to a smaller head diameter compared to adults. Wong et al. has shown that the doses to paediatric patients from head CT could be reduced by as much as 250% relative to adults by reducing the mAs and still obtain essentially the same image-to-noise ratio [19]. Unfortunately, most institutions do not reduce the exposure to children or other patients with reduced body size to save patient dose.

A comparison of the applied scan parameters for the three most frequently used CT scanners may give the opportunity to evaluate to what extent optimization to CT scanner and patient size had been carried out at HUH (table III). Different mean mAs values were applied for the examinations of children on the three scanner models, but its significance is questionable due to large standard deviations. To evaluate if a scanner specific calibration have been done, radiation output and detector efficiency for the scanners must be known. Tabulated values for CTDI\(_{\text{air}}\) showed that radiation outputs were identical. Further, an assumption of increased detector efficiency of the newer GE scanner (GE HiSpeed Advantage) compared to the older one (GE 9800) is realistic. Based on this, the observed reduction in applied mAs when the old GE scanner were replaced by the new one in 1995 (table I), indicate that scanner specific mAs calibration is performed to some extent at HUH. No significant reduction in applied mAs when scanning babies compared to children were observed for the two GE scanners. However, a reduction in applied mAs of almost 50% was observed for the Philip LX scanner. Again the significance of this reduction is questionable due to the large standard deviation. Based on the absence of applied paediatric protocols for the two GE scanners the observed reduction in mAs on the Philip scanner is assumed to be random, indicating that cerebral CT examinations at HUH is not optimised.
5. Conclusions

During the study period, children with shunt treated hydrocephalus underwent frequent head CT examinations throughout their lives, resulting in potential high accumulated effective doses, lens doses and brain doses. Since children have an increased risk of lifetime cancer mortality and the brain doses received by most of these children exceeded the threshold dose for cognitive reduction in adulthood, an optimization of the CT examinations are important, especially for paediatric patients.

References