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Abdominal Pediatric Cancer Surveillance using Serial CT: Evaluation of Organ Absorbed Dose and Effective Dose

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Abstract

Computed tomography (CT) is used extensively in cancer diagnosis, staging, evaluation of response to treatment, and in active surveillance for cancer reoccurrence. A review of CT technology is provided, at a level of detail appropriate for a busy clinician to review. The basis of x-ray CT dosimetry is also discussed, and concepts of absorbed dose and effective dose are distinguished. Absorbed dose is a physical quantity (measured in milliGray) equal to the x-ray energy deposited in a mass of tissue, whereas effective dose utilizes an organ-specific weighting method which converts organ doses to effective dose measured in milliSieverts. The organ weighting values carry with them a measure of radiation risk, and so effective dose (in mSv) is not a physical dose metric but rather is one that conveys radiation risk. The use of CT in a cancer surveillance protocol was used as an example of a pediatric patient who had kidney cancer, with surgery and radiation therapy. The active use of CT for cancer surveillance along with diagnostic CT scans led to a total of 50 CT scans performed on this child in a 7 year period. It was estimated that the patient received an average organ dose of 431 mGy from these CT scans. By comparison, the radiation therapy was performed and delivered 50.4 Gy to the patient's abdomen. Thus, the total dose from CT represented only 0.8% of the patient's radiation dose.

Introduction

Computed tomography (CT) imaging has come under scrutiny^{1,2} recently due to its increased use³ and high radiation levels². Although the majority of patients undergoing CT have from 1 to 3 CT studies, some patients have many CT scans over the course of an illness or injury. For patients recovering from cancer, however, some cancer surveillance protocols call for several CT scans per year, for many years. A survey of CT use at our institution suggested that about 5% of patients who have had a CT scan have had over 20 CT scans³, where each CT scan is defined by a unique Current Procedural Terminology (CPT) code. Although the average patient had 2.88 CT scans and the median was 4 scans per patient, patients in cancer surveillance protocols can have 20, 30, or even 40 or more CT scans.

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The use of CT in pediatric patients is of heightened concern, because younger patients are thought to be more radiosensitive and moreover, they have greater potential longevity, which increases the chance that a radiogenic tumor would manifest. Radiation acts to amplify cancer incidence, especially for highly-prevalent cancers. Therefore, radiation received during abdominal or thoracic CT scans contributes to higher cancer risk per unit radiation dose than scans in other parts of the body (e.g. head), because of the higher incidence of abdominal-thoracic cancers such as lung, colon, breast, prostate, and pancreatic cancers.

Overview of CT Technology

CT scanners have increased in complexity since their introduction clinically in 1972. There have been several fundamental design changes over the decades, which have improved the speed of acquisition as well as the image quality of modern CT systems. Today, all CT scanners make use of a powerful x-ray tube mounted on a CT gantry, opposite to a multi-detector array of x-ray detectors (Fig 1). The x-ray tube and detectors are mounted on the same rigid gantry and rotate together in unison. The electrical components on the moving gantry are connected to stationary electrical components by use of multiple slip rings, which allow power to be supplied to the rotating components and signals to be conveyed to stationary computers near the CT gantry. The slip ring connections eliminate the need for wire connections between the rotating gantry and stationary CT frame, and thus the gantry is untethered and rotates continuously in one direction during a CT acquisition. Rotation times for the gantry are now down to 0.33 seconds per rotation – 3 rotations per second or 180 rotations per minute.

Modern CT scanners are capable of both *axial* and *helical* acquisition. In axial acquisition, the x-ray source trajectory is that of a true circle around the patient. Axial acquisition is achieved with the patient stationary while the x-ray tube and detector system rotate around the patient, (usually) over a 360° rotation. The x-ray tube is briefly deactivated while the patient table advances by a small distance (~20 – 40 mm) under motor control, and then another axial acquisition is made. This process is repeated until the entire anatomy of interest is scanned. With helical acquisition modes (also called spiral), the patient is translated continuously through the CT gantry while the x-ray gantry rotates around the patient. This acquisition mode results in the x-ray source trajectory being that of a helix located around the patient.

Because helical acquisition modes do not require the repeated stop and start sequences during the scan that axial scanning uses, helical CT allows very rapid acquisition and thus very short acquisition times. For example, a helical CT scan of the thorax (~25 cm) and abdomen (~20 cm) combined require only 11 seconds on a modestly equipped CT scanner (20 mm detector array and 0.5 sec rotation), which is well within a breath-hold interval for most patients. The speed of acquisition is one of the principal reasons why CT has become so widely used for diagnostic imaging.

During a CT scan, the CT hardware acquires millions of measurements of x-ray transmission through the patient (Fig 2). This data is reconfigured in the computer using a reconstruction algorithm called filtered backprojection, resulting in a series of CT images. The native reconstruction plane of the data is trans-axial; however, the CT image data can be reconfigured into coronal, sagittal, and other orientations through the patient as well. The CT images can represent quite narrow sections through the body, with 0.5 mm to 0.625 mm being the narrowest sections on most current CT scanners. With these dimensions, the 45-cm abdominal-thorax scan mentioned above would entail 900 images at 0.5 mm section thickness (usually depicted as being along the “z-axis” of the patient), with each image being 512 × 512 picture elements (pixels). For a typical axial field of view of 35 cm, the

pixel dimensions in the x-y plane of the patient would be ~ 0.68 mm (350 mm / 512), and thus each volume element (voxel) produced in this CT acquisition would have dimensions of $0.68 \times 0.68 \times 0.50$ mm – very close to being isotropic, i.e., the same dimension in each direction. The 45-cm abdominal-thoracic scan previously mentioned would result in over 184 million voxels, with each voxel corresponding to ~ 230 μ g of unit-density tissue.

The CT image data are reconstructed with very small voxels, and therefore the images have excellent spatial resolution (Fig 3). But what does the gray scale in CT images correspond to? Because CT images are produced by x-ray attenuation, the gray scale in CT images is related to the tissue properties that affect x-ray attenuation for the x-ray energies used in CT. The most obvious tissue property that is reflected on CT images is that of tissue density. Air, both inside and outside the body, has negligible density and appears black on CT images, while other tissues such as the liver are more dense (density ~ 1 g/cm³) and appear gray; adipose in the body is slightly less dense and appears as darker gray. X-ray attenuation is strongly dependent on atomic number as well as density. Thus, the gray scale of bone is much whiter than soft tissues, partly because bone is denser than soft tissue but also because bone is calcified, and calcium has a higher atomic number ($Z=20$) than the elements that comprise soft tissue (when averaged, $Z \approx 7.6$). Iodine-containing contrast agents have very high atomic number ($Z=53$) and thus can appear extremely white, depending on the dilution factor that occurs as the iodine is distributed by the vascular system after intravenous injection. The gray scale values in CT are called Hounsfield Units (HU) in honor of Godfrey Hounsfield, co-inventor of CT and co-winner of the 1979 Nobel Prize for Medicine with Alan Cormack. The HU scale is normalized such that when water is scanned, $HU = 0$.

Overview of Concepts in Radiation Dosimetry

Because x-ray attenuation is the basis of image formation in CT, there is a necessary deposition of x-ray energy in the patient, which results in the deposition of radiation dose to the tissues being scanned. Radiation dose is defined as the absorbed energy (Joule) per unit mass (kg), and the units of radiation dose are therefore Joule/kg, which is also defined as the Gray (1 Gy = 1 Joule/kg). A typical single abdominal CT scan will lead to a dose of about 5 – 10 mGy to the abdomen, and smaller doses are deposited to the tissues away from the scanned volume by x-ray scattered radiation. Many CT protocols call for multiple CT scans to be acquired at the same time (typically before and after contrast agent injection), and thus CT dose increases linearly when two or more CT scans are performed during the same scanning session.

Radiation absorbed dose (“dose”) in the units of mGy represents a physically measureable quantity (energy/mass), and medical physicists typically use computer modeling techniques to compute the radiation dose deposited to a number of organs during a given CT scan or other x-ray imaging procedure. The x-ray organs of primary interest in x-ray dosimetry are given in Table 1:

The effective dose (ED) is used by the medical community to assess the relative risk associated from a given x-ray imaging procedure such as CT. Determining effective dose requires that the radiation dose (in mGy) be computed to a number of different organs and tissues (listed in Table 1), and then a weighting factor is applied to these doses. The unit of effective dose is the Sievert (Sv) or more commonly, mSv. The product of the organ dose (in mGy) and the weighting factor (units of mSv/mGy) is the effective dose for that tissue (mSv), and the sum of effective doses from all irradiated tissues is the *total effective dose* for that imaging procedure. Let’s use the example of the 5 mGy typical of two-view screening mammography, where only the breasts are irradiated. To compute effective dose, the breast organ dose (5 mGy) is multiplied by the W_t for the breast (Table 1, $W_{\text{breast}} = 0.12$), resulting in an effective dose of 0.6 mSv. The example of mammography involved only one organ,

but CT can deposit radiation dose in any number of organs and tissues, depending on the location of the CT scan (e.g., head, abdomen, pelvis, etc). For CT, all the organs that received radiation dose are included in the calculation, and the total effective dose is the sum of these values. The effective dose⁴ uses a weighting system based on the radiation risk estimates developed from exposed human populations⁵.

The weighting factors for each tissue type in Table 1 were derived from epidemiological data resulting from the Japanese Atomic bomb survivors, and thus these W_t factors reflect the variation in radiation carcinogenesis for each organ or tissue type. These values were computed from long-term radiation epidemiological studies of these large, irradiated human populations. While the effective dose concept is not without detractors, it does provide a methodology of assessing the radiation risk from CT scanning and other imaging procedures involving ionizing radiation. The effective dose also allows one to compare the radiation risk between different imaging procedures, such as radiography of the head versus CT of the head.

Illustration of radiation dose from CT surveillance in one pediatric cancer patient

The radiation dosimetry for a pediatric patient who underwent 50 CT scans at our institution under a cancer surveillance program is explored in detail, and with institutional review board approval, the organ dose distribution and effective dose were tallied. The individual organ doses for each CT scan were computed using a computer-based spreadsheet designed for this⁶, and the effective dose was also calculated. The radiation dose levels reported here are thought to be illustrative of CT doses in some patients undergoing cancer surveillance, and may provide clinically relevant guidance to other physicians involved in long-term serial CT imaging of pediatric patients.

Patient History and Treatment—The 6-year-old patient presented in December 1999 with an abdominal mass and pain. After biopsy, the boy underwent neoadjuvant chemotherapy, and a right nephrectomy was performed. The pathology per the National Wilms Tumor Study Pathology Center determined the tumor to be a high grade renal sarcoma, not otherwise specified. He was then treated under POG protocol 9151, regimen 47. Initial metastatic workup revealed a right upper lobe nodule that ultimately resolved. No other metastases were seen. His therapy was complicated by multiple episodes of neutropenia. Nearly 3 years after his initial diagnosis, the patient suffered a recurrence of his tumor in periaortic lymph nodes, which was surgically resected. Further chemotherapy and local radiation therapy (50.4 Gy) were given for this recurrence, and these therapies were completed in July 2003. The patient has been off therapy, but has been carefully monitored and imaged since that time. Initially he was scanned by CT every three months (5 visits), then every six months (5 visits), and currently he is undergoing CT surveillance on a yearly basis.

Patient Radiation Therapy—The patient received radiation treatment of 50.4 Gy in 28 fractions to the paraaortic tumor bed beginning in February 2003. He was treated with 18 MV photon beams from a Varian Clinac 2100C linear accelerator (Varian Medical Systems, Palo Alto, CA). The first 45 Gy were delivered using opposed AP/PA beams, with a 5.4 Gy boost delivered with parallel-opposed oblique beams. His treatment was interrupted for a week during week #5 due to neutropenia, thrombocytopenia, and severe diarrhea requiring hospitalization. Treatment was resumed when his health status recovered and his diarrhea was under control. Radiation treatment was completed in March 2003.

CT Scan History—The patient was aged 14 in January 2008, and had a history of CT scans beginning in December 1999 at age 6. Fifty CT scans were performed over this period.

The most recent CT scan evaluated in this study was performed in February 2006. The patient had reached adult dimensions in the most recent scans, and abdominal CT scan measured 32.5 cm laterally and 19.0 cm in the antero-posterior dimension. The 50 CT scans were acquired on 23 different non-contiguous dates, and thus each CT scanning session involved an average of 2.2 CT scans. Earlier CT scans (26 of the 50) were performed on a single detector array helical CT scanner (HiSpeed CT/i, General Electric Medical Systems, Waukesha, WI), and scans performed after April 2003 (24 of 50) made use of a 16-detector array CT scanner (Lightspeed-16, General Electric Medical Systems, Waukesha, WI).

CT dosimetry—Each of the 50 CT scans was evaluated using the picture archiving and communication system (PACS) at our institution (iSite Radiology, Philips Medical Systems, Eindhoven, Netherlands), and the technical factors associated with each scan including kVp, mA, exposure time per rotation, helical pitch, collimation, slice thickness, and time of acquisition were recorded in a spreadsheet (Excel, Microsoft Corporation, Redmond, WA). The CT scan images were evaluated (DL) using the PACS system to determine the location of the scanned region in the body, and these position values were then entered into an Excel spreadsheet-based dosimetry tool developed by the ImPACT group in the United Kingdom⁷. Fig 4 illustrates the graphical tool that is used to position the CT scan start and stop locations on the ImPACT software. The ImPACT dose tool uses Monte Carlo-based dosimetry data coupled with an extensive set of output measurements of CT scanners, including those used in this study. Individual organ absorbed doses were computed from the CT scanning procedure. The dose calculations took into consideration the kVp, beam shaping filter, scanner geometry, and output levels of the scanner, including mA, rotation time, and pitch. The location in the body of each of the scans was also carefully estimated to determine the scan location on the dosimetry software.

The quantity *effective dose* is useful in prorating the cancer risk in partial-body irradiation procedures typical of medical imaging to whole-body irradiation events, specifically to the well-studied Japanese atomic bomb survivors⁸. The detailed analysis of ED in this study allowed the assessment of the relationship between dose length product (DLP) and ED^{9,10,11,12,13}. The dose length product (DLP) was estimated using the volume computed tomography dose index (CTDI_{vol}) and the CT scan length¹⁴. The ED computed from the spreadsheet computations were made, and the relationship between ED and DLP was assessed.

CT Dose Evaluation Results

The absorbed dose to abdominal organs is shown in Fig 5, as a function of CT scan. The varying dose levels to each of the organs from scan to scan are due, in part, to different CT technique factor selection, however, the most important factor that influences the specific organ dose is the position of the scan field of view for each individual CT scan. Adjustments in the inferior and superior edges of the scanner's field of view will have a large impact on specific organs, as these edges define the extent of the primary radiation beam in the patient. The high doses to the stomach and liver for scan 14 correspond to a high mAs, low pitch study for high resolution images.

Fig 6 illustrates the absorbed doses to thoracic organs as a function of CT scan number. The high thymus doses for scans 21–22–23 correspond to a head CT scan.

The total effective dose for each CT scan is illustrated in Fig 7. The ED values that dip below 4 mSv correspond to high resolution, short-length (small field of view) acquisitions or head CT scans (which result in lower ED values due to the lower tissue weighting coefficients in the head).

Fig 8 illustrates the total absorbed dose from all 50 CT scans to each of the organs evaluated in this study. The average organ dose was 431 mGy ($\sigma = 190$ mGy).

Fig 9 demonstrates the relationship between the effective dose computed from abdominal and pelvic CT studies with dose length product (DLP). The DLP (product of the scan length (in cm) and the CTDI_{vol}) and the ED were computed for 20 abdominal or pelvic CT scans which employed the multi-detector array CT scanner only. Excellent agreement ($r_2 > 0.99$) was seen between DLP and ED, and the slope of this line (with zero intercept) is $0.0147 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$.

The total effective dose from all 50 CT scans was 413 mSv.

Discussion

CT provides clinicians with a convenient imaging tool for monitoring patients who may be likely to develop tumors subsequent to the initial discovery and treatment of a primary cancer. Many surveillance protocols call for frequent CT imaging procedures, and this can lead to high accumulated radiation levels in patients undergoing surveillance. In an example presented in this review, a pediatric patient was diagnosed and treated for primary kidney carcinoma, including unilateral right-kidney resection and ultimately radiation therapy. The radiation therapy treatment delivered an absorbed dose of 50.4 Gy to the patient's abdomen. Thus, the average organ dose of 431 mGy due to the serial CT scanning represents only 0.85% ($0.431 / 50.4$) of the radiation dose received by this patient.

The detailed analysis of this patient's CT scanning dose history has shown that the frequent CT imaging of the patient over a period of over seven years has lead to a cumulative effective dose of 413 mSv, or approximately 8.3 mSv per CT scan.

The benefit / risk consequences of the radiation dose due to CT may be different in the absence of radiation therapy. For example, the total accumulated background ED for this patient over the 7 years of clinical follow-up was approximately 23.1 mSv, assuming 3.3 mSv per year as the background radiation level. In this case, the dose due to CT would represent 95% ($413 / 436.1$) of the patient's effective dose. While there should be substantial concern for secondary radiation-induced cancers under aggressive CT surveillance protocols in the absence of radiation therapy, this case has shown for patients who have undergone treatment with radiation therapy, that aggressive CT surveillance has contributed to less than 1% of the radiation burden to this patient.

The relationship between DLP and ED demonstrated excellent correlation ($r_2 > 0.99$) over 20 relevant CT scans, and the conversion factor was $0.0147 \text{ mSv (mGy cm)}^{-1}$ or $14.7 \text{ } \mu\text{Sv (mGy cm)}^{-1}$. This value compares quite well with those estimated for pediatric patients by Huda⁹ which range between 16.0 to 19.0 $\mu\text{Sv (mGy cm)}^{-1}$. The value also compares well with the conversion factors of about 17 $\mu\text{Sv (mGy cm)}^{-1}$ for various abdominal CT procedures as reported in European guidelines¹⁵. The DLP to ED conversion factor is often used to estimate effective dose from the dose length product (DLP) which is documented on the CT scanner for a given CT examination.

Conclusions

The basic operation of a modern CT scanner was described. The example of a pediatric patient enrolled in a CT cancer surveillance protocol for cancer reoccurrence was used to show the relative dose from CT compared to radiation therapy. This patient had 50 CT scans over 7 years. The radiation dose from each scan was computed, and the average organ dose was 8.5 mGy and the total ED from all 50 scans was approximately 413 mSv. While this ED

was approximately 18 times background radiation levels, the radiation therapy received by this patient still represents over 99% of the total radiation dose. It is observed that aggressive cancer surveillance protocols in pediatric patients contribute negligibly to the overall risk of secondary cancer induction for patients who have received radiation therapy.

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Fig 1. The geometry of the x-ray source and detector system in a modern CT scanner is illustrated. The gantry rotates around the patient and collects the projection data that is used to compute the CT images.

Fig 2.

The CT scanner hardware collects millions of data in order to produce the CT images. Views are acquired at each location of the x-ray tube as it makes its rotation around the patient, and each view is comprised of >1000 rays. Each CT image is typically computed from over 1 million rays. Each ray conveys information about the x-ray attenuation properties of the patient, and when combined using a reconstruction algorithm, a two dimensional map of x-ray attenuation is produced for each image—the CT image is a scaled version of the attenuation map.

Fig 3.

The gray scale values in CT are called “Hounsfield Units” (HU), in honor of CT pioneer Godfrey Hounsfield. The HU of water is defined as zero, and air is $HU = -1000$. Air appears black on CT, and soft tissue such as the liver appears gray. Bone as well as tissues perfused with iodine-based contrast agents appear very white under normal display conditions.

Fig 4.

The ImPACT CT dose tool allows the user to position the location of the CT scan along a “body” which is composed of mathematical shapes which were used for the Monte Carlo dose assessment.

Fig 5.
The abdominal organ absorbed doses are illustrated for each imaging session for the 50 CT scans.

Fig 6.

The absorbed dose to thoracic organs is illustrated for the 50 CT scans.

Fig 7.

The effective dose (ED) is illustrated for each of the 50 CT scans. The ED metric combines the dose from all organs with tissue-specific weighting factors, and the total ED from all organs is plotted here. The CT scans which demonstrate very low ED levels (scans 8, 17, 37, 38, 41, and 45) correspond to very small scan lengths in the patient, while the low ED values for scans 21–23 correspond to a head CT scan.

Fig 8.

The absorbed dose to each of the organs assessed is illustrated in this bar chart. Organ doses for the 50 CT scans range from 114 mGy (11.4 Rads) for the thyroid to 872 mGy (87.2 Rads) to the remainder tissues.

Fig 9.

The relationship between Dose Length Product (DLP) and Effective Dose is shown for 20 CT scans performed in the abdomen or pelvis on the multi-detector array CT scanner. The slope of this line is the “k-factor” often used for CT dosimetry, and here this value is 0.0147 mSv / mGy-cm. Excellent correlation between effective dose and DLP is seen.

Table 1

The organs and tissues used in radiation dosimetry, and the tissue weighting factors (W_t) used for computing effective dose (ICRP 103 values).

Organ or Tissue	W_t factors
Gonads	0.08
Bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.04
Breast	0.12
Liver	0.04
Esophagus	0.04
Thyroid	0.04
Skin	0.01
Bone surface	0.01
Brain	0.01
Salivary Glands	0.01
remainder	0.12