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THE ROLE OF TECHNOLOGISTS IN COMPUTED TOMOGRAPHY PATIENT DOSE OPTIMIZATION

By

Thaddeus L. Morris

A thesis

submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Physics

Idaho State University

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To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Thaddeus L Morris find it satisfactory and recommend that it be accepted.

_____

Dr. Richard Brey, Major Advisor

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Dr. Jason Harris, Committee Member

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Dr. Dewayne Derryberry, Graduate Faculty Representative

IRB EXEMPTION LETTER

NOTICE OF EXEMPTION FROM IRB REVIEW

To: Thaddeus Morris
Via email: Thaddeus.Morris@CoxCollege.edu

From: Kathleen Jackson, IRB Chair

Date: September 19, 2014

This letter is to advise you that the project you are requesting to conduct titled "Patient Dose Management in Computed Tomography" does not require review by the CoxHealth Institutional Review Board (IRB). This project does not meet the definition of research.

It is my understanding that the intention of this project is to analyze the occurrences of "high dose" CT procedures including an understanding of why they occur. You indicate your goal is to determine if process improvements can be undertaken to reduce or even prevent future occurrences. Because the main focus of this project is to improve the care that we provide patients potentially reducing safety risk, the IRB considers this a Quality Improvement project involving a process within the hospital.

You should remain mindful of HIPAA rules and if at all possible this project should be conducted without obtaining patient identifiers. However, if patient identifiers will be used to conduct this project, they should be kept in a secure manner, such as an encrypted flash drive. They should be destroyed as soon as possible. You may be required to document in patient accounts reason for access.

Please notify the IRB office of any changes made in the conducting of this project, intentions of use of findings, or any other pertinent information. Changes made may result in a non-exempt status of your project making you noncompliant with government regulations.

We wish you success in your project and look forward to working with you on future projects. Please contact Cortney Freeman if you need further assistance or there is anything else the IRB may help you with. She may be contacted at (417) 269-7669 or via email at Cortney.Freeman@CoxHealth.com.

KJ/cf

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ABSTRACT

Multiple agencies and organizations have initiated processes to optimize patient dose from computed tomography (CT) and establish diagnostic reference levels (DRLs) for CT and other imaging modalities. This study supports those initiatives by seeking to establish high-dose thresholds for common CT procedures and quantify the extent to which correctable technologist decisions result in high patient doses. The study considered four examination types at one institution: CT Adult Head without Contrast, CT Pediatric Head without Contrast, CT Abdomen and Pelvis without Contrast for Renal Stone, and CT Angiography Chest for Pulmonary Embolism. One hundred (100) examinations were reviewed for each examination type amounting to 400 total samples. Data collected for each patient included age, weight, image noise, CTDI, and DLP. High-dose thresholds for each examination type were set at the upper limit of each data set but below apparent outliers. Additional methods were attempted for setting high-dose thresholds but without success. Normalization of the dose data based on patient weight and image noise was performed, but this transformation did not prove helpful in identifying genuine high-dose examinations. In total, 67 of 400 examinations were identified as meeting the high-dose criteria for non-normalized data. Of these examinations, 27% (18 of 67) were caused by correctable technologist decisions. This represented 4.5% of all examinations investigated. When projected for different examination populations, the mean technologist error rate is calculated as 4.9% ± 2.1%.

CHAPTER 1: INTRODUCTION

1.1. OBJECTIVES

The overarching objective of this project is to define the extent to which correctable technologist actions result in detectable overexposure to the patient. Additionally, this research attempts to create an algorithm through which high-dose cases can be distinguished from other causes of high dose outside of the control of the technologist. To this end, the following objectives will be addressed:

1. Define average patient absorbed dose (mGy) for routine computed tomography examinations – CT Adult Head without Contrast, CT Pediatric Head without Contrast, CT Abdomen and Pelvis without Contrast for Renal Stone ("*CT Renal Stone*"), and CTA Chest for Pulmonary Embolism ("*CT PE*")
2. Define the relationship between subject thickness (patient weight) and absorbed dose
3. Define the relationship between absorbed dose and image noise (standard deviation)
4. Define an algorithm for normalizing patient absorbed dose based on patient weight and image noise
5. Define "high dose" threshold for routine CT examinations
6. Define and quantify causes of high-dose in computed tomography

1.2. IDENTIFICATION OF ISSUES

Patient dose management and patient dose reduction is a growing concern in diagnostic imaging and, in particular, computed tomography (CT). Several national organizations have joined the effort to address this issue. As an example, *The Joint Commission* (TJC) has recently released

several mandates directed towards moderating and reducing patient dose from computed tomography and other diagnostic imaging procedures (TJC 2013). These mandates include:

1. Minimum competency for radiology technologists, including registration and certification by July 1, 2015
2. Annual performance evaluations of imaging equipment by a medical physicist
3. Documentation of CT radiation dose in the patient's clinical record
4. Meeting the needs of the pediatric population through imaging protocols and considering patient size or body habitus when establishing imaging protocols
5. Management of safety risks in the MRI environment
6. Collection of data on incidents where pre-identified radiation dose limits have been exceeded

We are concerned with mandate #6, the collection of data on CT examinations which have exceeded a pre-defined threshold. Since dose varies considerably with patient size, this effort could be greatly enhanced by creating an algorithm that defines dose as a function of patient size. This will be an empirical equation developed using regression analysis.

Concerns related to patient dose management in computed tomography may be summarized by four observations: 1) computed tomography (CT) imaging procedures deposit relatively large doses of ionizing radiation in the range of 1 to 15 mSv, 2) the use of CT for medical imaging is increasing, 3) dose from CT imaging is associated with hypothetical increases in the incidence of cancer, and 4) specific practices and habits of imaging technologists have a measurable effect on patient dose.

1.3. HYPOTHESES

Concerning the relationship between subject thickness and absorbed dose:

1. Null Model: A linear relationship exists between subject thickness and dose.
2. Alternate Model: A non-linear relationship exists between subject thickness and dose.
3. Decision Rule: The best model will be identified as having the lowest Akaike Information Criterion (AIC) score.

Concerning the relationship between absorbed dose and CT image noise (standard deviation):

1. Null Model: A linear relationship exists between dose and image noise.
2. Alternate Model: A non-linear relationship exists between dose and image noise.
3. Decision Rule: The best model will be identified as having the lowest Akaike Information Criterion (AIC) score.

Concerning the normalization of patient dose:

1. Null Model: Normalizing patient dose will not increase the total number of high-dose examinations demonstrating a correctable technologist action.
2. Alternate Model: Normalizing patient dose will increase the total number of high-dose examinations demonstrating a correctable technologist action.
3. Decision Rule: The best model will be identified as that which demonstrates the most high-dose examinations associated with a correctable technologist action.

Concerning the causes of high-dose:

1. Null Hypothesis: Correctable technologist decisions do not show a measurable increase in the number of high-dose examinations.
2. Alternate Hypothesis: Correctable technologist decisions show a measurable increase in the number of high-dose examinations.

3. Decision Rule: All examinations exceeding a pre-defined high-dose threshold will be reviewed for technologist errors. Results will be projected for different examination populations with a confidence interval using Wilson's estimators.

CHAPTER 2: LITERATURE REVIEW

2.1. DOSE IN CT

The standard indicator of patient absorbed dose during a CT imaging procedure is the CTDI – computed tomography dose index. Measured in milligray (mGy), CTDI represents the average dose per section thickness normalized over the length of the scan (McNitt-Gray 2002). CTDI is estimated for a given set of scan parameters by scanning a tissue equivalent cylinder phantom with one or two ionizations chambers inside. There are several methods for calculating CTDI, but only one is endorsed by the Food and Drug Administration (FDA) and required on all commercial CT scanners. 21 CFR 1020.33 specifically states: *"Computed tomography dose index (CTDI) means the integral of the dose profile along a line perpendicular to the tomographic plane divided by the product of the nominal tomographic section thickness and the number of tomograms produced in a single scan."* This is calculated as:

$$CTDI = 1/nT \int_{-7T}^{+7T} D(z)dz \quad (2.1)$$

Where:

z = position along a line perpendicular to the tomographic plane

D(z) = Dose at position z

T = Nominal tomographic section thickness

n = 7, the number of tomograms produced in a single scan

This definition assumes that the dose profile is centered around z = 0 and that, for a multiple tomogram system, the scan increment between adjacent scans is nT. The FDA does allow for an alternative calculation, $CTDI_{100}$, in which case the dose profile is measured and integrated over 100 mm to accommodate more common calibration instruments (FDA 2014).

A related concept is the dose linear product (DLP), which is equal to the CTDI multiplied by the total scan length in centimeters. DLP is provided in mGy-cm (McNitt-Gray 2002). CTDI is useful for comparing exposure between patients even when the scan parameters (scan length) might be different. Conversely, DLP is more useful in identifying the effective dose (E) and estimating biological effects (AAPM 2008). There is some debate over whether or not CTDI should be used as an indicator of absorbed dose. McCollough et al (2011) argue that CTDI does not reflect patient absorbed dose and therefore should not be used to project biological hazards. Nonetheless, CTDI remains as the only standardized method for estimating patient dose from CT scan parameters. Minimally, CTDI is a value correlated to patient dose from CT imaging procedures and is therefore useful index to patient dose.

The absorbed dose for any given CT scan is extremely variable. Factors affecting patient dose include scan type (axial or helical), technical factors (mA, kVp, and exposure time), scan length, the anatomic section being imaged, the patient's size, and the habits of the technologist (McNitt-Gray 2002). Columbia University reports average CTDI and DLP across several scanner configurations and vendors for major CT protocols (Table 2.1).

Table 2.1. Reported average patient absorbed dose for major CT protocols at Columbia University, New York.

Scan type	CTDI (mGy)	DLP (mGy-cm)	Effective Dose (mSv)
Adult head	59.7	1044.3	2.19
Adult neck	14.9	223.8	1.32
Adult abdomen	14	310.6	5.25
Adult pelvis	14	310.6	5.25
Pediatric abdomen	8.5	126.9	2.70
Adult chest	8.4	294.0	4.12

The absorbed dose in Table 2.1 is generated from these scanner types: Siemens Volume Zoom 4, Siemens Sensation 4, Siemens Sensation 10, Siemens Sensation 16, GE Lightspeed 64 VCT, GE Lightspeed Pro, and a Philips Spect-CT (Columbia University).

The effective dose from common CT scans range from 1 to 15 mSv per scan. By comparison, this is as much as 100 times the effective dose of a conventional radiograph (AAPM 2008) or as much as 5 times the annual dose received from natural background radiation to the average North American (NCRP 160, 2012). CT alone accounts for about 25% of the non-occupational radiation dose received by the average North American each year (NCRP 160, 2012).

2.2. DOSE THRESHOLDS

Appropriate exposure levels in CT are often described in terms of "Diagnostic Reference Levels" (DRLs). The IAEA (2013) explains that, *"Diagnostic reference levels (DRLs) are a practical tool to promote the assessment of existing protocols and appropriate development of new and improved protocols at each CT centre by facilitating the comparison of doses from present practice. DRLs were first successfully implemented in relation to conventional X rays in the 1980s and subsequently developed for application to CT in the 1990s."* As explained by McCollough (2010), DRLs are not intended to describe ideal dose levels or even maximum dose, but should simply represent the dose at which point an investigation of the exposure should be initiated. The general philosophy is that DRLs are set to the 75^{th} percentile of the dose distribution as surveyed from a broad user base. National DRLs have not yet been established in CT, but the practice of establishing DRLs has been shown to reduce both the mean dose and standard deviation of imaging procedures (McCollough 2011). The establishment of local and national DRLs enables a facility to compare their patient doses to those of other facilities.

Dose thresholds for CT procedures are currently published by the American College of Radiology (ACR) and required for imaging facilities accredited by the ACR. These values are

listed in Table 2.2. ACR accreditation criteria are intended only to represent the typical technical factors used at a facility and therefore do not currently encompass all examinations types.

2.3.

Table 2.2. ACR dose management requirements.

Examination	Pass/Fail Criteria CTDI (mGy)	Reference Levels CTDI (mGy)
Adult Head	80	75
Adult Abdomen	30	25
Pediatric Head	40	35
Pediatric Abdomen	20	15

DOSE NORMALIZATION

The process of "dose normalization" is a tool that may be used to distinguish between the different causes of high dose examinations: *large patient size* versus *technologist.* Normalization defines an "appropriate" dose versus and "inappropriate" dose even when comparing patients of very different size. If the relationship between dose, weight, and image noise are linear, the expression for normalization is:

$$Normalized\ Dose = Actual\ Dose\ x\ \left(\frac{Mean\ Weight}{Actual\ Weight}\right)\left(\frac{Mean\ SD}{Actual\ SD}\right) \qquad (2.3.1)$$

where "SD" is the standard deviation of the image, representing the image noise and image quality. The SD term is necessary to scale down the dose for large patients who have reached the maximum tube output for a given protocol. This will also scale up dose for smaller patients who might have received an needlessly large dose resulting in especially low image noise.

The normalization process is used to identify situations in which an error or anomaly resulted in additional dose, rather than high dose caused by patient size. Non-linear relationships, such as polynomial or exponential, are also possible. Due to the known exponential relationship between radiation attenuation and subject thickness, it is also possible that the data might demonstrate an exponential relationship between thickness and dose. The same may also be true

when the relationship between standard deviation and dose is defined. In this case the expression for normalization could be:

$$Normalized\ Dose = Actual\ Dose\ x\ \left(\frac{e^{-0.167\ x\ (mean\ weight)}}{e^{-0.167\ x\ (actual\ weight)}}\right)\left(\frac{e^{0.167\ x\ (mean\ SD)}}{e^{0.167\ x\ (actual\ SD)}}\right) \quad (2.3.2)$$

In this expression, 0.167 corresponds to the linear attenuation coefficient (cm^{-1}) of water or tissue equivalence. The actual normalization expression is calculated from experimental data investigated in this study.

2.4. ONCOLOGICAL RISK FROM CT

The consensus of modern research is that effective dose from computed tomography examinations is projected to result in an increase in the number of future cancers. Berrington de Gonzalez et al (2009) and Brenner et al (2001) each conducted extensive studies attempting to predict oncogenesis based on age, sex, scan type, and other relevant factors. Brenner et al focus on CT scans on the pediatric population while Berrington de Gonzalez et al include a comprehensive analysis of all CT procedures performed in a given year (2007). Both studies are built around the age-dependent model published by the National Academy of Sciences Biological effects of Ionizing Radiation committee (BEIR VII). In both models (and in both studies) the effective risk of future cancers from CT exposures assumes a linear extrapolated risk from intermediate doses to low doses. This extrapolation is necessary since cancer mortality data from radiation exposures is derived from Japanese atomic bomb survivors, most of which received much higher doses than those typically received from CT procedures.

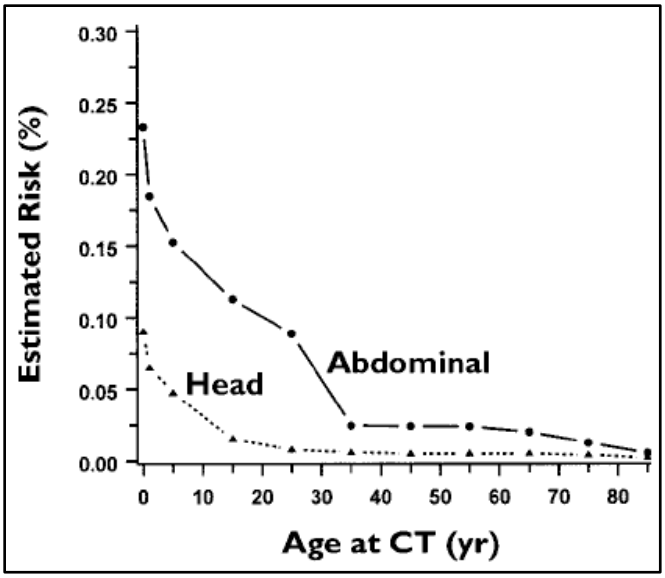

Figure 2.4.1. Lifetime attributable cancer mortality risk as a function of age at examination. Data is plotted for a single typical CT examination of head (broken dotted line) and of abdomen (broken solid line) (Brenner et al 2001).

Berrington de Gonzalez et al concluded that CT scans performed in 2007 would be expected to result in 29,000 new cases of cancer during the lifetime of the exposed patients. This estimate gave consideration to situations in which the diagnosis for the CT scan was an existing cancer and reduced the projection according. The same kinds of corrections were applied to scans performed on elderly patients (within 5 years of expected death). A dose rate effectiveness factor was also applied to scans below 100 mGy. Assuming 50% cancer mortality, this study also projected 14,500 cancer deaths from CT procedures performed in 2007.

The research of Brenner et al is based on older data, but the conclusions are similar. This study emphasizes that the dose and risk for pediatric patients is higher than that for adult patients. There are numerous reasons for this, including: 1) scanning protocols are not routinely changed for smaller patients, 2) dose to smaller patients is higher than that to larger patient for the same exposure factors due to the nature of radiation absorption, and 3) children are more radiosensitive than adults. Brenner et al reduced their research to the most common studies: CT

Head and CT Abdomen. Results are noted in Figure 2.4.1. This research estimated cancer mortality in the United States based on data extrapolated from a different study in Britain and applied it only to CT Head and CT Abdomen scans. They estimated 2,500 total cancer deaths from CT scans performed in the United States, presumably for the year 2001 when the paper was published. Four hundred and eighty (480) of these deaths would be expected to result from scans performed on children (<15 years old). They acknowledge this number is exceedingly low, only 0.35% over the background cancer rate. Percent contribution of pediatric cancers to the total population varied between the studies. Brenner et al estimate this value at 20% for children 15 and younger while Berrington de Gonzalez et al estimate 15% from patients 18 and younger.

A related study was completed by Huda and Vance (2006). The objective of this study was to define typical organ doses and associated effective doses to adult and pediatric patients from single CT exposures. Unlike Brenner et al and Berrington de Gonzalez et al, Huda and Vance do not attempt to project cancer risk. Instead, their work helps to define the *actual* patient dose (mGy) per scan type according to the patient weight and tube output. Brenner et al, Berrington de Gonzalez et al, and others have based patient dose on the Computed Tomography Dose Index (CTDI), but the research of Huda and Vance show that CTDI is expected to under- and over-estimate actual dose based on the patient size. There are several causes for this error. CTDI is calculated for only two phantom sizes, 16 cm (diameter) and 32 cm. The calculation also normalizes the dose index over 10 cm, which is often less than actual scan limits. Huda and Vance demonstrated that for the average adult patient, correcting for patient size would increase CTDI by approximately 50% for abdominal scans and 100% for chest scans. This is demonstrated in Figure 2.4.2. This affects the research of Brenner et al and Berrington de

Gonzalez et al since their work assumes patient adsorbed dose is equal to the CTDI. The extent to which their epidemiological data might be altered by scaling dose per patient size is unknown.

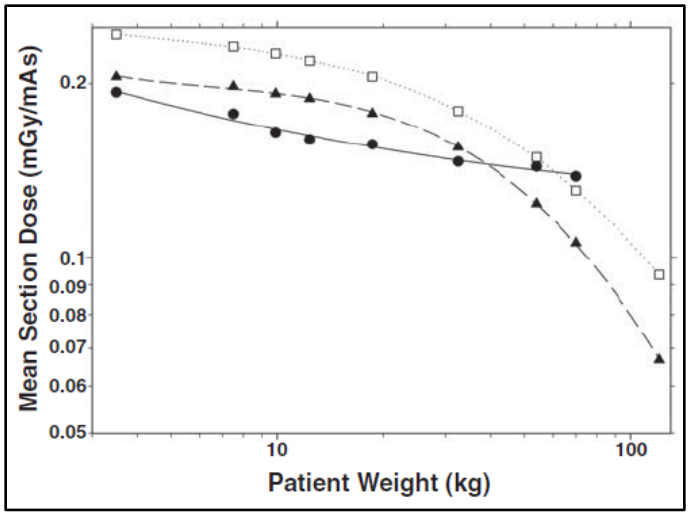

Figure 2.4.2. Mean section dose versus patient weight for CT examinations. Dose of head (solid line), chest (dotted line), and abdomen (dashed line), where curves are least square fits to a second order polynomial (Huda and Vance 2006).

All three studies describe specific mechanisms for reducing patient dose (whether collectively or individually) and thereby reducing the incidence of cancer caused by CT procedures. Tube current has a linear relationship with patient dose, so any fractional reduction in tube current will reduce dose in the same way. Modifications to pitch and scan limits show the same relationship. For example, doubling the pitch ration reduces the dose by half. Decreasing the total scan length by 10% would decrease DLP (mGy-cm) by the same amount. The relationship between kVp and dose is not linear. Huda and Vance (2006) note that increasing tube potential (kVp) for a fixed current increases patient absorbed dose by a factor of five.

Berrington de Gonzalez et al do acknowledge the large degree of uncertainty associated with these oncological projections. To date, cancer risk from CT scans have not been

demonstrated directly, and doing so would require a large-scale long-term study (Berrington de Gonzalez et al 2009). The authors also acknowledge that their projections are based on the linear no-threshold model, which is provided for radiation protection purposes but is not designed for use in epidemiological projections. With the current data available, actual carcinogenesis as a consequence of CT imaging is statistically undetectable. These estimates are expected to be extreme over-estimates of the actual endemic rate.

2.5. CT PATIENT DOSE OPTIMIZATION

Dose optimization is the practice of minimizing patient radiation dose while maintaining the image quality necessary for diagnosis. Optimization generally includes fitting the imaging parameters to the specific size, shape and age of the patient and ensuring a degree of continuity between protocol types. The FDA is working to enhance patient dose optimization by advocating for national radiation dose tracking registries and data bases (FDA 2014). This effort has first required that the FDA work with device manufacturers to ensure imaging equipment is capable of automatically recording patient dose, protocol parameters, and patient information in standardized formats. This effort comes with specific objectives, including:

1. Providing information at the point-of-care for the referring practitioner
2. Promoting development and use of diagnostic reference levels (DRLs)
3. Providing information for assessment of radiation risks
4. Establishing a tool for use in research and epidemiology

To this end, the FDA is working with stakeholders in the area of radiation dose optimization, including: the Conference of Radiation Control Program Directors (CRCPD), the National Council on Radiation Protection and Measurements (NCRP), the American College of Radiology (ACR), and many more organizations and agencies (FDA 2014).

The immediate need for dose optimization is further evident in the rapid growth of CT use in recent years. CT is on the forefront of acute stroke imaging, traumatic injury assessment, cancer diagnosis and numerous other pathologies. Nearly 70 million scans are performed each year and, not surprisingly, that number is on the rise. (Harvey 2012). In Emergency Departments, for example, the use of CT scans per patient encounter increased 330% between 1996 and 2007 (Kocher 2011).

Several methods are well-established as being central to optimizing dose in CT, some of which are highly dependent on the technologist. These include: 1) limiting the region scanned to the smallest area possible, 2) and adjusting the technical factors (mA, kVp) to the size of the patient (Colang et al 2007). Many scan parameters are built into default protocols loaded onto the scanners, but most of these defaults can be manually overridden by the technologist at their discretion.

CHAPTER 3: MATERIALS AND METHODS

3.1. SCANNERS AND DATA SOURCES

All data for the study was drawn from two General Electric (GE) Lightspeed 16 slice CT scanners located at the same facility. The examination data was drawn from one scanner or the other for any individual protocol assessment. Protocols and reprocessing algorithms are believed to be identical between the scanners, but as an additional safeguard to protect data quality the data was purposeful not compared between scanners. Dose data on specific scans was collected from the institutional picture archiving and communication system (PACS).

3.2. DEFINING THE NORMALIZATION FUNCTION

The scanner was set to automatically increase mA (tube output) based on subject thickness, in this case the number of acrylic blocks. The variable mA setting ("auto-mA") was employed with kVp fixed at 120. The first acrylic block was set on end and stabilized using the scanner immobilization straps. The first localizer image obtained was in the anterior-posterior (AP) projection and the second in the lateral projection. The block was scanned with slice thickness set at 2.5 mm using the standard algorithm. The following information was documented: mA, CTDI, DLP, and the standard deviation of the CT numbers taken from an ellipse ROI in center of the image. This same procedure was performed a total of 7 times with each repetition including an additional block. Each block measured 2.2 cm x 30.5 cm x 30.5 cm. In the last scan, 7 total blocks were scanned. This data was plotted to describe CTDI as a function of phantom thickness. A regression line was defined and this information was used to create the patient weight component of the normalization expression.

Standard deviation (image noise) was also defined as a function of dose. In this case the subject thickness was fixed at 7 acrylic blocks (15.4 cm). kVp was fixed at 120. Tube output was initially set at 50 mA and increased by intervals of 25 up to 225 mA. A total of 9 scans were performed with CTDI, DLP, and standard deviations collected for each scan. This data was graphed and the standard deviation component of the normalization function was defined. The process was performed for both helical and axial scanning modes.

3.3. DEFINING HIGH DOSE THRESHOLDS

Examination data and dose information was retrieved on 100 procedures for four different examination types, resulting in 400 total samples. Examination types ("protocols") considered are:

- CT Adult Head without Contrast (patient age > 18 years)
- CT Pediatric Head without Contrast (patient age < 5 years)
- CT Abdomen and Pelvis without Contrast for Renal Stone
- CTA Chest for Pulmonary Embolism

These examinations represent a range of complexity and increasing opportunity for technologist error. Scan information was collected from the institution's PACS database. The information documented for each scan in each protocol type included:

- Examination Identification (ID) Number
- Patient Weight (kg)
- Standard Deviation (SD) in an ROI
- CTDI (mGy)
- DLP (mGy-cm)

Examination ID was recorded as the patient's birthdate and stored securely. This information was tracked so that examinations defined as high dose could be evaluated retrospectively. Weight is the mass of the patient documented in kilograms. CTDI and DLP were recorded and reported exactly as provided by the scanners, which often included five or six significant figures. The actual precision of these values is not known, but the non-normalized data was assessed without rounding the dose information. SD was acquired for each examination type in a specific tissue type in the scan using a ROI. This value was assumed to represent the image noise of the exam. ROI position was specific to the scan type:

- CT Adult Head without Contrast – Standard deviation for adult head was drawn from an ROI placed in the pons at its widest point away from any artifact in the 2.5-mm slices
- CT Pediatric Head without Contrast – Standard deviation for pediatric head was drawn from an ROI place in the pons at its widest point away from any artifact in the 2.5-mm slices
- CT Abdomen and Pelvis without Contrast for Renal Stone – Standard deviation was drawn from an ROI placed in the spleen at the level of the kidneys
- CTA Chest for Pulmonary Embolism – Standard deviation was drawn from an ROI placed in the liver at the level of the kidneys in the 2.5-mm slices

Data from the spreadsheet was used to define mean CTDI, mean DLP, and mean standard deviation for all examination types. Various methods were used to identify an appropriate dose threshold level for each examination type. Mean plus 2 standard deviations, mean plus 30%, and arbitrary identification of outliers were all attempted. For two protocols, CT Renal Stone and CT PE, the process was repeated after application of the normalization functions defined in 3.2.

High-dose examinations were identified as those exceeding the defined high dose threshold and/or appearing as an apparent outlier compared to patients of similar size. The identification of high-dose examinations was done before and after normalization for both CTDI and DLP. Changes in CTDI are most indicative of changes in exposure settings such as milliamperage (mA), kilovolt potential (kVp), rotation time, or pitch. DLP is a function of CTDI but is equally affected by scan length, a parameter manually set by the technologist for each patient.

3.4. RETROSPECTIVE ANALYSIS OF HIGH DOSE EXAMINATIONS

Apparent high-dose examinations were scrutinized for the cause of over-exposure. It was expected that only a small fraction (<10%) of all examinations would demonstrate a verifiable technologists error resulting an over-exposure. This is because all technologists at this institution are credentialed in CT and protocols are generally very prescriptive in an effort to avoid errors. Each high-dose examination was analyzed and categorized as one of the following: no identifiable cause ("no cause"), change in kVp/mAs setting, large patient, repeated examination series, over-scan, or other. Results were compared between normalized and non-normalized data in order to assess the usefulness of the normalization expression. "Over-scan" refers to situations in which the technologist extended the scan beyond the recommended boundaries of the protocol. Mean technologist error rate and the associated confidence interval were estimated using Wilson's Estimators, where:

$$Mean\ Error\ Rate\ (\acute{p}) = \frac{y+2}{n+4} \tag{3.4.1}$$

and the confidence interval is calculated as:

$$\acute{p}\ \pm 1.96\ x\ \sqrt{\acute{p}\ x\ (\frac{1-\acute{p}}{n+4})} \tag{3.4.2}$$

where n is equal to the sample size and n is equal to the number fitting the description.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. NORMALIZATION EXPRESSION

4.1.1. NORMALIZATION FOR PATIENT THICKNESS

Actual dose modulation per subject thickness using auto-mA is recorded in Table 4.1.1. The associated graph of this data and potential regression lines are represented in Figure 4.1.1.

Table 4.1.1. Actual dose modulation per subject thickness using auto-mA. kVp was fixed at 120 and mA was modulated according to the scanners automatic mA modulating software.

Phantom Thickness (cm)	kVp (fixed)	mA (variable)	CTDI (mGy)	SD
2.2	120	9	0.5	37.2
4.4	120	86	4.7	13.2
6.6	120	152	8.3	16.5
8.8	120	124	6.8	21.3
11	120	132	7.3	30.5
13.2	120	160	8.9	26.5
15.4	120	207	11.4	28.2

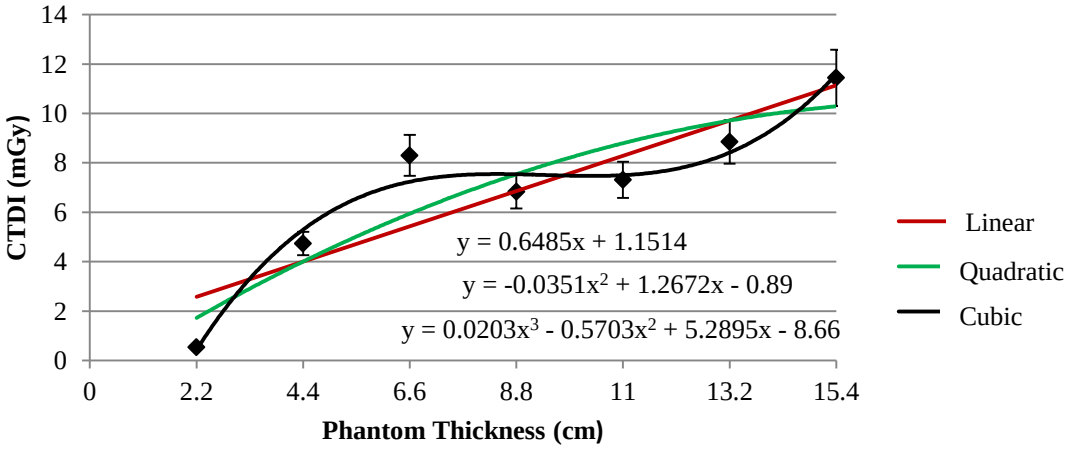

Figure 4.1.1. Actual dose modulation per subject thickness using auto-mA. Uncertanty is assumed as ±10% of the measured value.

Several regression lines may be applied to fit this data, none of which perfectly agree with theoretical expectations. The relationship is directly proportional, but not exponential in nature. Notably, the average image noise (standard deviation within an ROI) had a mean of 24.76

Hounsfield Units (HU) with a standard deviation of 6.66 HU. Dose modulating software is designed to maximize image quality while minimizing dose, but the image noise (standard deviation) still varied considerably between scans. This brings into question the usefulness of normalizing patient dose based on the image noise. Dose to be applied to the patient is determined prospectively based on the attenuation properties of the lateral localizer image.

Possible regression lines to fit the data include:

- Linear: $y = 0.6485x + 1.1514$ where $R^2 = 0.7951$ and $AIC = 32.8$
- Polynomial 2nd Order (quadratic): $y = -0.0351x^2 + 1.2672x - 0.89$ where $R^2 = 0.829$ and $AIC = 45.5$
- Polynomial 3rd Order (cubic): $y = 0.0203x^3 - 0.5703x^2 + 5.2895x - 8.66$ where $R^2 = 0.9693$ and $AIC = 75.6$

Using Akaike's Information Criterion, the linear model is identified as having the best predictive value for normalizing dose according to patient weight. The resulting normalization term for patient weight is therefore:

$$Normalized\ Dose = Actual\ Dose\ x\ \left(\frac{Mean\ Weight}{Actual\ Weight}\right) \qquad (4.1.1)$$

4.1.2. NORMALIZATION FOR IMAGE NOISE

The effect of increasing dose on standard deviation (image noise) is recorded in Table 4.1.2. The associated graph of this data is represented in Figure 4.1.2.

Table 4.1.2. CTDI as a function of image noise for helical scan types. Phantom thickness is fixed at 15.4 cm and kVp is set to 120.

Phantom Thickness (cm)	kVp (fixed)	mA (variable)	CTDI (mGy)	SD
15.4	120	50	2.7	71.9
15.4	120	75	4.1	54.0
15.4	120	100	5.4	44.1
15.4	120	125	6.8	31.9
15.4	120	150	8.2	30.4

Phantom Thickness (cm)	kVp (fixed)	mA (variable)	CTDI (mGy)	SD
15.4	120	175	9.5	30.8
15.4	120	200	10.9	29.3
15.4	120	225	12.2	24.3
15.4	120	250	13.6	24.6

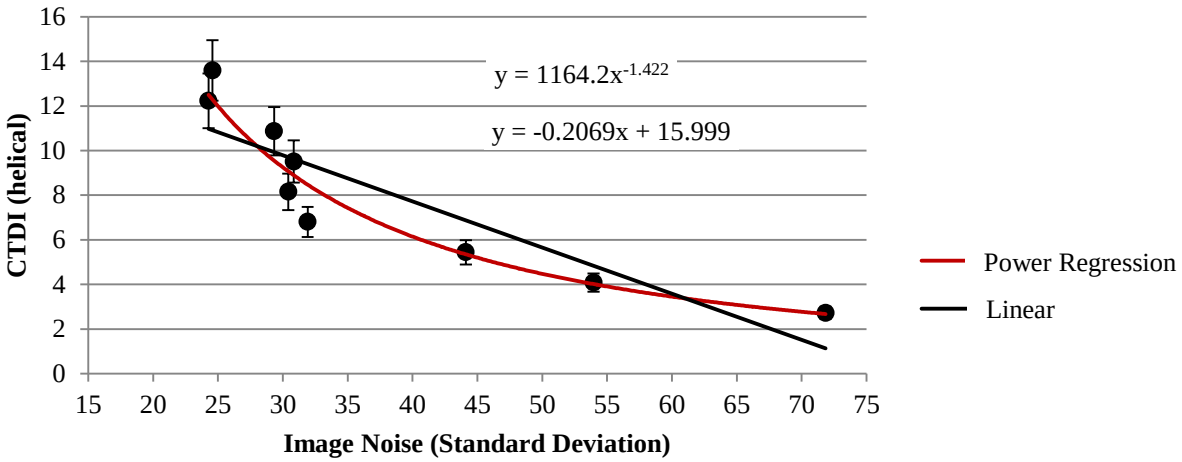

Figure 4.1.2. CTDI as a function of image noise for helical scan types. Uncertainty is assumed as ± 10% of the measured value.

These data sets were fit with a power regression equation and linear model. Using Akaike's Information Criterion, the power regression model is identified as having the best predictive value for normalizing dose according to the image noise.

- Power Regression: $y = 1164.2x^{-1.422}$ *where* $R^2 = 0.9597$ *and AIC = 28.2*
- Linear: $y = -0.2069x + 15.999$ *where* $R^2 = 0.784$ *and AIC = 36.2*

Based on the information collected, the normalization expression for *helical* scans is:

$$Normalized\ Dose = Actual\ Dose\ x\ \left(\frac{Mean\ Weight}{Actual\ Weight}\right)\left(\frac{Mean\ SD^{1.422}}{Actual\ SD^{1.422}}\right) \qquad (4.1.2)$$

Image noise is seen to be highly variable between scans (mean = 24.8; standard deviation = 6.7). The usefulness of the SD term in the normalization expression is therefore suspect. Because of these observations, a modified expression was applied and evaluated:

$$Normalized\ Dose = Actual\ Dose\ x\ \left(\frac{Mean\ Weight}{Actual\ Weight}\right) \quad (4.1.2.b)$$

in which the SD term is eliminated completely.

CT Head protocols were not normalized since the CTDI and DLP showed very limited variability and dose did not correlate with patient weight. Additionally, the preset CT head protocols at this facility use a fixed mA setting (not auto-mA), meaning the tube output only changes if the technologist overrides the initial settings. As a consequence, dose for these protocols does not change predictably with patient weight and varies only with changes in the total scan length. As an example, Figure 4.2.1 shows that nearly 50% of all CT adult head examinations have identical CTDI values and Figure 4.2.2 shows DLP values are identical for nearly 70% of all adult head examinations.

4.2. CT ADULT HEAD WITHOUT CONTRAST

CTDI data is graphed in Figure 4.2.1. Examinations were numbered in the order in which the data was retrieved. The high dose threshold (red line) is set at 75 mGy, which is equal to the ACR reference level for this protocol. Incidentally, the mean CTDI (69.4 mGy) plus 2s (s = 2.8 mGy) is also equal to 75 mGy. A value equal to the mean plus 30% was given considered as a threshold value, but this value (90.2 mGy) is above the ACR recommendation.

DLP data is graphed in Figure 4.2.2. Examination numbers correspond with the same patients as in Figure 4.2.1. The high dose threshold for this dose parameter was set at 1,200 mGy-cm. As is visible on the graph, the majority of scans (67 of 100) listed a DLP value of 1,160 mGy-cm. Given this strong bias in the data all examinations exceeding this value (1,160 mGy-cm) were identified as a high dose examination and analyzed. Values of 2 standard deviations (2s) above the mean (1410 mGy-cm) and 30% above the mean (1520 mGy-cm) were

given consideration as potential threshold values, but in both cases these values seemed to excluded apparent outliers from the high dose criteria.

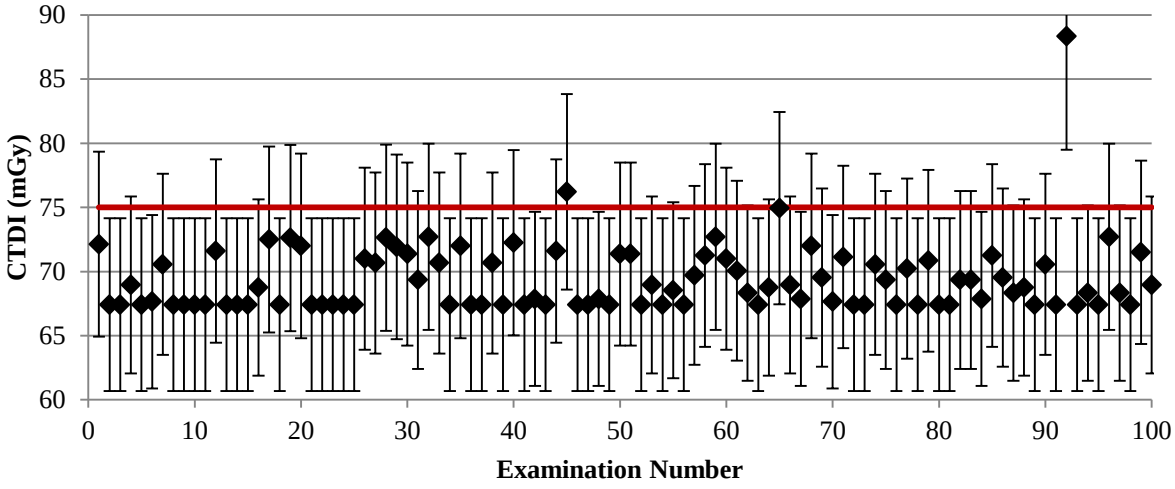

Figure 4.2.1. Adult head CTDI per examination number. Uncertainty is assumed as ± 10% of the measured value. High-dose threshold (red line) is set at 75 mGy, which is equal to the ACR recommendation.

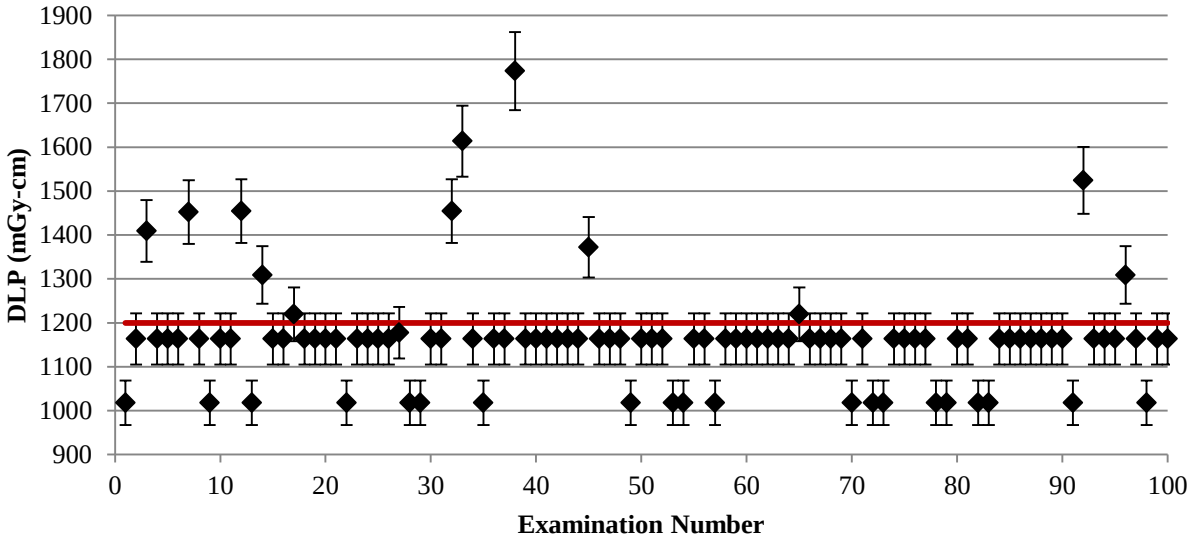

Figure 4.2.2. Adult head DLP per examination number. Uncertainty is assumed as ± 10% of the measured values. High-dose threshold (red line) is set at 1,200 mGy-cm, which is just beyond the apparent upper limit of the data (1,167 mGy).

High dose examinations based on the CTDI threshold for CT Adult Head are listed in Table 4.2.1. Causes of high dose are also recorded.

Table 4.2.1. Causes of high-dose (CTDI) for CT adult head examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
45	X					
92				X		

High dose examinations based on DLP threshold for the CT Adult Head protocol are listed in Table 4.2.2. Causes of high dose are also recorded.

Table 4.2.2. Causes of high-dose (DLP) for CT adult head examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
3			X			
7			X			
12			X			
14					X	
17						X
32			X			
33			X			
38			X			
45			X			
65						X
92				X		
96			X			

Both high-dose examinations exceeding the CTDI threshold also exceeded the DLP threshold. Several additional examinations are identified as being high-dose based on the DLP threshold. This is not surprising since DLP quantifies dose from repeated series and over-scans while CTDI does not; however, both dose parameters provide useful information describing the dose to the patient. Examination 45 exceeded the CTDI threshold due to selection of a specific protocol (“fast scan”) which was preset into the machine. Examinations 17 and 65 exceeded the DLP threshold because the orientation of the patients head in the gantry required that the scan be

extended further than normal. Orientation of the head in the gantry is assumed to be a correctable by the technologist. A summary of the causes of high-dose examinations is provided in Table 4.2.3.

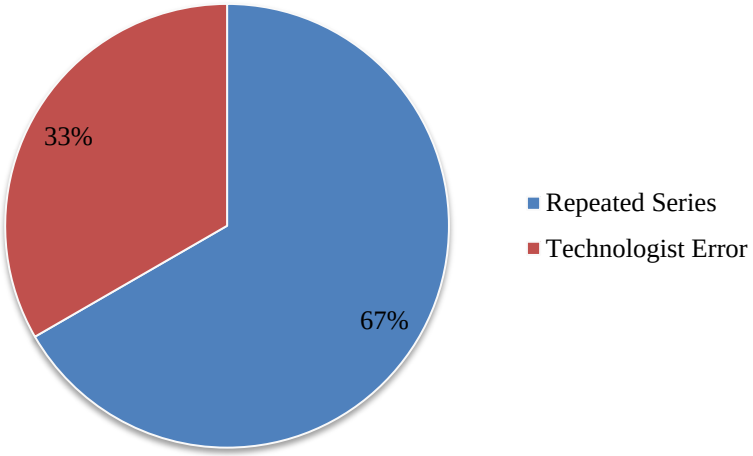

Figure 4.2.3. Causes of high-dose CT adult head examinations. Technologist errors included: overs-scan, technique changes, and patient orientation.

4.3. CT PEDIACTRIC HEAD WITHOUT CONTRAST

The CT pediatric head data set included patients ages newborn (NB) through 4 years. This cohort includes two slightly different protocols. NB through 18 month patients are scanned with a protocol using 115 mA tube current. The protocol for patients ages 18 months through 5 years uses a tube current set at 140 mA. The data has a slight stair-step appearance around the 18 month threshold (Figure 4.3.1.).

CTDI for the CT Pediatric Head is graphed in Figure 4.3.1. Examinations were number in the order in which the data was retrieved, which in this case corresponded to the patient age at the time of scanning. The high dose threshold (red line) is 35 mGy, which is equal to the ACR reference level for the pediatric head protocol. An arbitrary threshold of 30% above the mean

was considered as a threshold value, but this value (42 mGy) is greater than the ACR recommendation. The same was true for a threshold set at 2 standard deviations (2s) above the mean (48 mGy).

DLP data is graphed in Figure 4.3.2. Examinations numbers correspond with the same patients as in Figure 4.3.1. The high dose threshold for this dose parameter was set at 500 mGy-cm, which is slightly beyond the apparent upper limit for most scans (472 mGy-cm). All examinations exceeding this value were identified as a high dose examination and analyzed. Arbitrary thresholds equal to 2s above the mean (885 mGy-cm) and 30% above the mean (672 mGy-cm) were given consideration as potential threshold values, but in both cases these values excluded apparent outliers from the high-dose criteria.

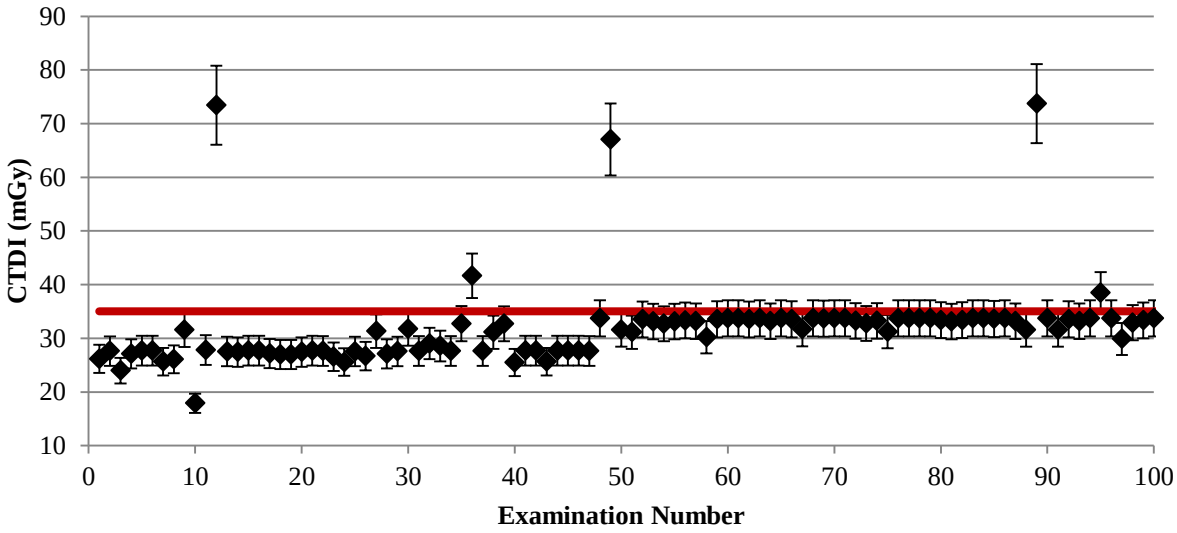

Figure 4.3.1. Pediatric head CTDI per examination number. Uncertainty is assumed as ± 10% of the measured value. High-dose threshold (red line) is set at 36 mGy, which is equal to the ACR reference level.

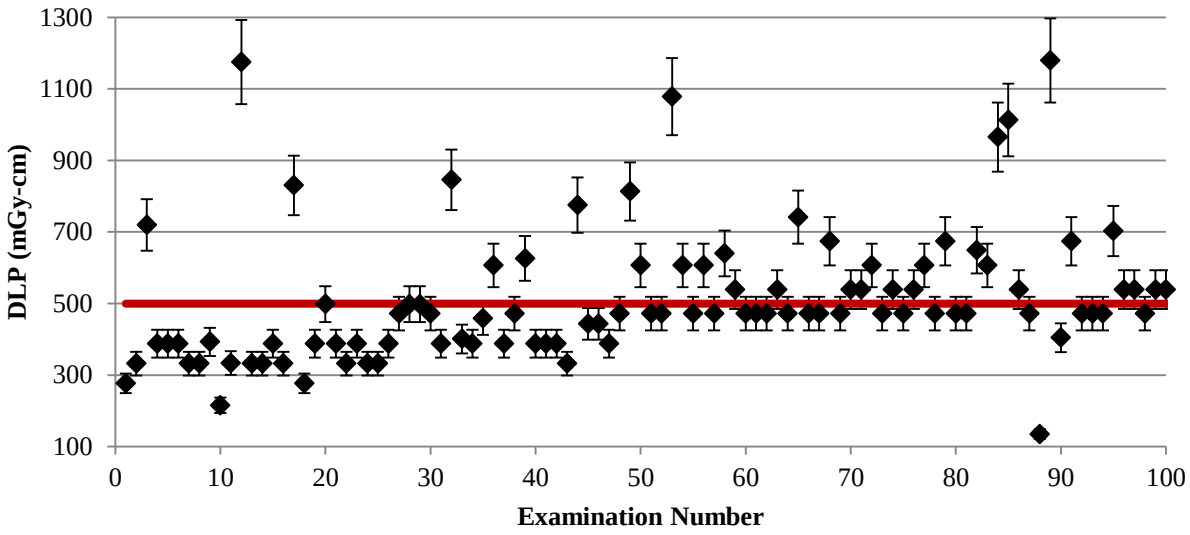

Figure 4.3.2. Pediatric head DLP per examination number. Uncertainty is assumed as ± 10% of the measured value. High-dose threshold is set to 500 mGy-cm, which is just beyond the apparent upper limit of the data.

High dose examinations based on the CTDI threshold for the CT Pediatric Head protocol are listed in Table 4.3.1. Causes of high dose are also recorded.

Table 4.3.1. Causes of high-dose (CTDI) for CT pediatric head examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
12				X		
36				X		
49				X		
89				X		
95				X		

High-dose examinations based on the DLP threshold for the CT Pediatric Head protocol are listed in Table 4.3.2. Causes of high dose are also recorded.

Table 4.3.2. Causes of high-dose (DLP) for CT pediatric head examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
3			X			
12			X	X		
17			X			
32			X			

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
36				X		
39			X			
44			X			
49				X		
50			X			
53			X			
54					X	
56			X			
58			X			
59	X					
63	X					
65			X			
68			X			
70			X			
71			X			
72			X			
74	X					
76	X					
77	X					
79			X			
82			X			
83			X			
84			X			
85			X			X
86	X					
89			X	X		
91			X			
95			X	X		
96			X			
97	X					
99	X					
100	X					

All high-dose examinations exceeding the CTDI threshold also exceeded the DLP threshold. Several additional examinations are identified as being high-dose based on the DLP threshold. All five examinations exceeding the CTDI high-dose threshold were the result of the technologist manually overriding the preset technique in the pediatric head protocol. In three of these cases the CTDI was more than double the average of all other examinations.

Examinations exceeding the DLP high-dose threshold totaled 36% of all examinations recorded (36 of 100). The majority of these high-dose examinations showed a repeated series caused by patient movement (24 of 36; 67%). Nine of the high-dose examinations (25%) showed no evidence of a technologist induced error or other cause, five (14%) were caused by mA/kVp changes, one (3%) was caused by over-scan, and in one case (3%) the technologist attempted two helical scans (for an unknown reason). Four examinations showed evidence of multiple errors – cases #12, 85, 89, and 95. A summary of the causes of high-dose CT pediatric head examinations is provided in Figure 4.3.3.

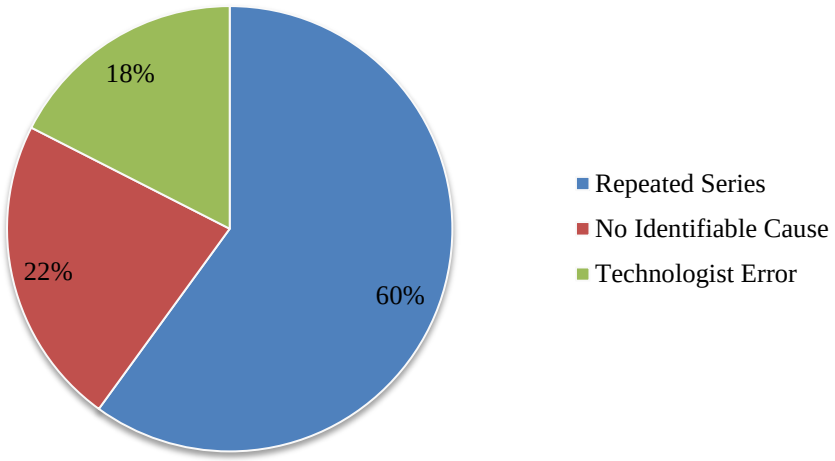

Figure 4.3.3. Causes of high-dose CT pediatric head examinations. Technologist errors included: overs-scan, technique changes, and repeated series with helical scanning. Four exams with repeated series also showed a technologist error.

4.4. CT ABDOMEN AND PELVIS WITHOUT CONTRAST FOR RENAL STONE

NON-NORMALIZED DATA

CTDI data is graphed in Figure 4.4.1. Examinations were numbered in order of increasing patient weight, which is why the CTDI values trend upward until they reach the preset maximum CTDI of 19 mGy. The high dose threshold (red line) is set at 20 mGy, which is just above the

apparent upper limit for the data set. The ACR reference level for an adult abdomen is 25 mGy, but setting the threshold at this level would exclude examinations from the high-dose criteria that are above the typical limit of the protocol (examinations #93 and #100). The inadequacy of this threshold is evident in that smaller patients could have been exposed to the maximum dose of this protocol and still not appear above the threshold. Lowering the threshold might capture these cases but as consequence the population of examinations identified as high-dose would also be cluttered by a significant number of large patients that were appropriately exposed at the maximum CTDI – hence the need for a normalization function to account for patients of different sizes.

DLP data is graphed in Figure 4.4.2. Examination numbers correspond with the same patients as in Figure 4.2.1. The high dose threshold for this dose parameter was set at 850 mGy-cm since the data appears to reach a plateau just below this level. Thresholds equal to 2s above the mean (1110 mGy-cm) and 30% above the mean (892 mGy-cm) were given consideration, but in both cases these values excluded apparent outliers from the high dose criteria. Even the assigned threshold of 850 mGy-cm excluded apparent outliers in the smaller patients (examination #5).

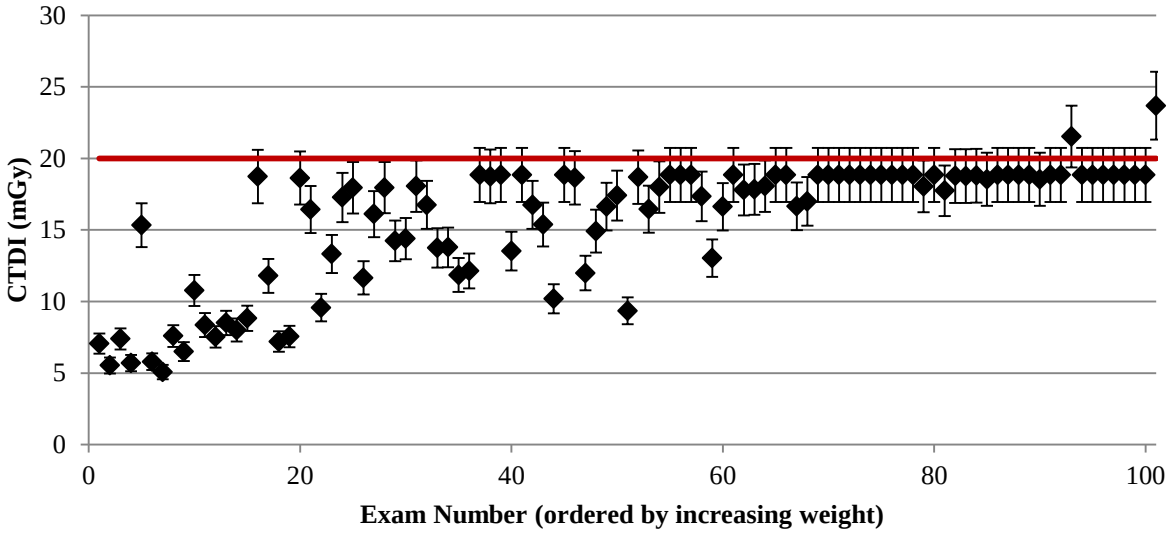

Figure 4.4.1. Renal stone CTDI per examination number. Uncertainty is assumes as ±10% the measured value. The high-dose threshold (red line) is set at 20 mGy, which is just beyond the apparent upper limit of the data.

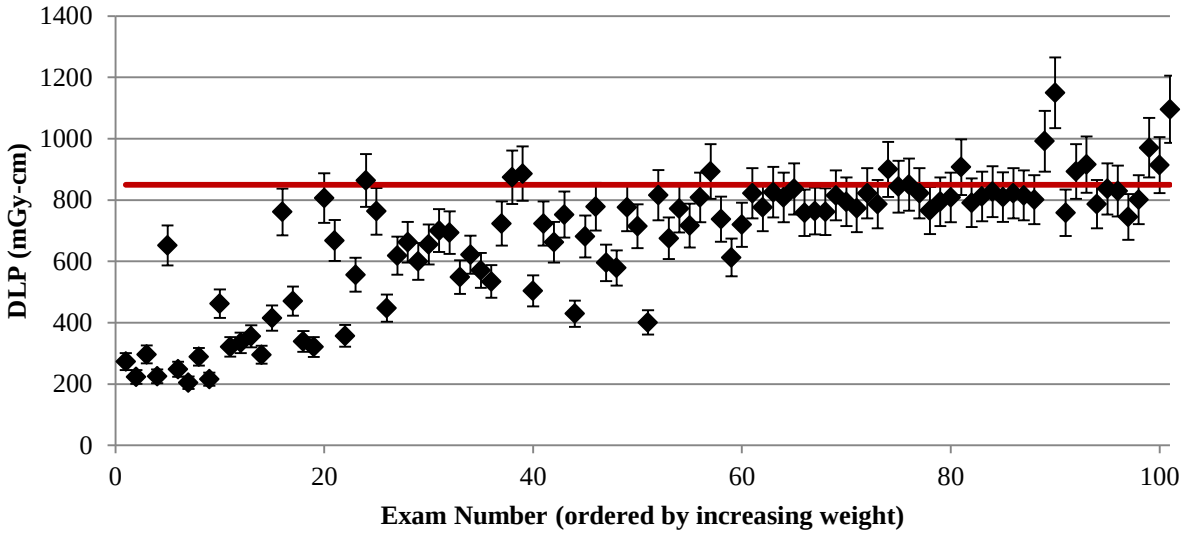

Figure 4.4.2. Renal stone DLP per examination number. Uncertainty is assumed as ± 10% of the measured value. The high-dose threshold is set to 850 mGy-cm, which is just beyond the apparent upper limit of the data.

High dose examinations based on the CTDI threshold for the CT Renal Stone protocol are listed in Table 4.4.1. Causes of high dose are also recorded.

Table 4.4.1. Causes of high-dose (CTDI) for CT renal stone examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
93		X		X		
100		X		X		

High dose examinations based on the DLP threshold for CT Renal Stone are listed in Table 4.4.2. Causes of high dose are also recorded.

Table 4.4.2. Causes of high-dose (DLP) for CT renal stone examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
24					X	
38					X	
39	X					
57	X					
74	X					
76	X					
81					X	
89					X	
90						X
92	X					
93		X		X		
99	X					
100		X		X		

Two examinations exceeded the CT Renal Stone CTDI threshold, both of which also exceeded the DLP threshold. Several additional examinations are identified as being high-dose based on the DLP threshold. Both examinations exceeding the CTDI threshold were the result of the technologist manually overriding the preset technique, presumably in an effort to maintain high image quality with especially large patients. Notably, this is not a consistent practice among technologists since only two of the ten largest patients received a technologist-modified dose. In both cases the image noise was superior to examinations of patients of similar size.

Examinations exceeding the DLP high-dose threshold totaled 13% of all examination recorded (13 of 100). The largest fraction of these high-dose examinations showed no obvious

cause or error (6 of 13; 46%). Four (31%) were caused by over-scanning, two (15%) were caused by filament current (mA) changes for larger patients, and one (8%) was caused by a unique protocol performed for a special diagnosis.

In summary, the majority of high-dose examinations (69%) showed no technologist error or identifiable cause. Examinations #93 and #100 are included in this assessment because the filament current (mA) was presumably changed with good cause. Four examinations (31%) were caused by the technologist scanning beyond the recommended boundaries of the protocol. This was 4% of all CT Renal Stone scans analyzed. A summary of the causes of high-dose examinations for the renal stone protocol is provided in Figure 4.4.3.

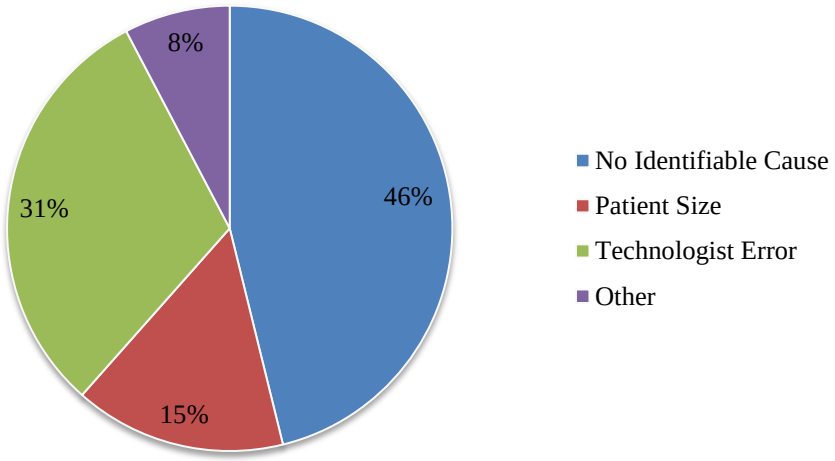

Figure 4.4.3. Causes of high-dose CT renal stone examinations. Over-scan was the only technologist demonstrated in this cohort.

NORMALIZED DATA: EQUATION 4.1.2

$CTDI_{norm}$ data for CT Renal Stone is graphed in Figure 4.4.4. Examinations were again numbered in order of increasing patient weight. The high dose threshold (red line) is set at 35 mGy, which is equal to mean plus 2s. A threshold equal to the mean plus 30% was also given consideration as a threshold (24 mGy) but this value identified 20 of 100 examinations as high-

dose, which was unreasonable when compared to other cohorts. The normalization function had the effect of increasing the mean from 15.8 mGy to 18.7 mGy and increased the standard deviation from 4.4 mGy to 8.3 mGy.

DLP_{norm} data for CT Renal Stone is graphed in Figure 4.4.5. Examinations were again numbered in order of increasing patient weight and correspond to the same patients as in Figure 4.4.3. The high dose threshold (red line) is set at 1500 mGy, which is equal to mean plus 2s. A threshold equal to the mean plus 30% was also considered (1000 mGy-cm), but this value identified nearly half of all examinations as high dose. The normalization function increased the mean from 686 to 796 and increased the standard deviation from 211 to 344.

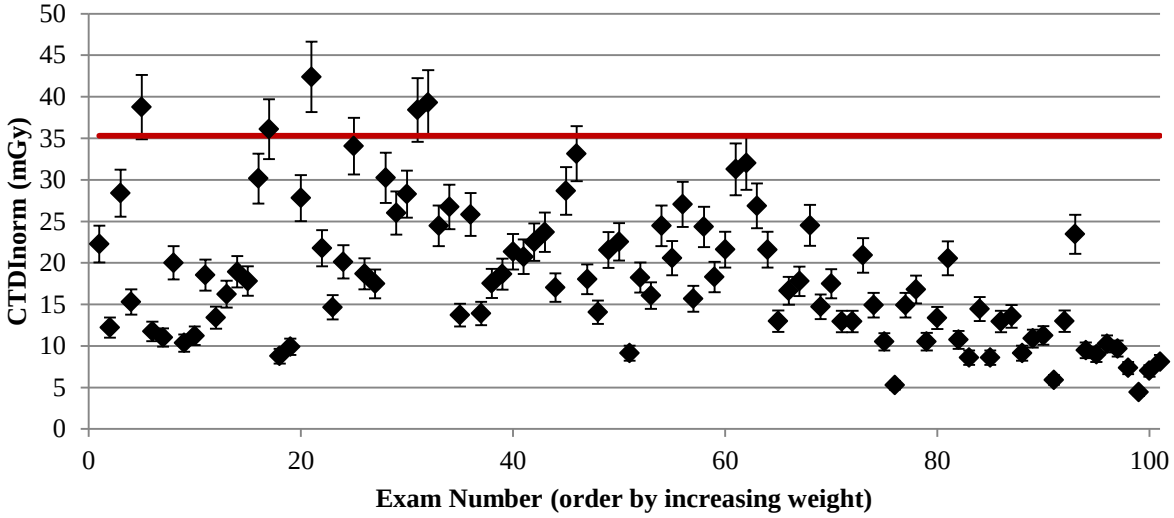

Figure 4.4.4. Renal CTDInorm per examination number. Uncertainty is assumed as ± 10% of the calculated value.

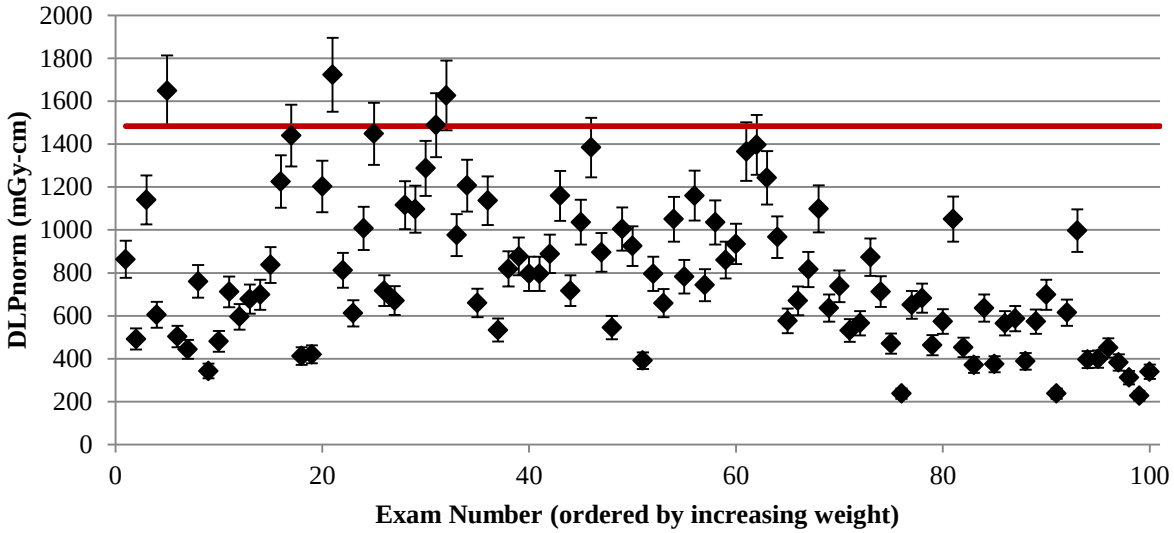

Figure 4.4.5. Renal stone DLP_{norm} per examination number. Uncertainty is assumed as ± 10% of the calculated value.

High dose examinations based on the $CTDI_{norm}$ threshold for the CT Renal Stone protocol are listed in Table 4.4.3. Causes of high dose are also recorded.

Table 4.4.3. Causes of high-dose ($CTDI_{norm}$) for CT renal stone examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
5	X					
17	X					
21	X					
31	X					
32	X					

High dose examinations based on the DLP_{norm} threshold for the CT Renal Stone protocol are listed in Table 4.4.4. Causes of high dose are also recorded.

Table 4.4.4. Causes of high-dose (DLP_{norm}) for CT renal stone examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
5	X					
31	X					
32	X					

After the normalization function was applied (4.1.2) five examinations exceeded the $CTDI_{norm}$ high-dose threshold and three examinations exceeded the DLP_{norm} threshold. All three examinations exceeding the DLP_{norm} threshold also exceeded the $CTDI_{norm}$ threshold. None of the five examinations identified as high-dose showed a verifiable technologist intervention or any cause at all. Examination #5 demonstrated an especially high CTDI and DLP, but the archived images did not confirm a cause. Causes might have included: 1) changing the noise-index, or 2) improper patient positioning in the gantry. Unfortunately, the normalized data did not capture the four over-scan examinations identified in the non-normalized data.

NORMALIZED DATA: EQUATION 4.1.2.b

$CTDI_{norm2}$ data for CT Renal Stone is graphed in Figure 4.4.6. This data transformation has a lower standard deviation than previous data sets and apparent outliers are more distinguishable. The high dose threshold (red line) was set accordingly at 23 mGy. This value is equal to two standard deviations above the mean.

DLP_{norm2} data for CT Renal Stone is graphed in Figure 4.4.7. The high dose threshold (red line) is set at 850 mGy-cm which is slightly beyond the apparent upper limit of the data. A threshold equal to two standard deviations above the mean was also given consideration (990 mGy-cm) but this value excluded examinations that stood out as apparent outliers. The normalization function had the same effect on DLP as it did on CTDI; specifically, the standard deviation decreased from 210 mGy-cm to 150 mGy-cm while the mean remained unchanged (690 mGy-cm).

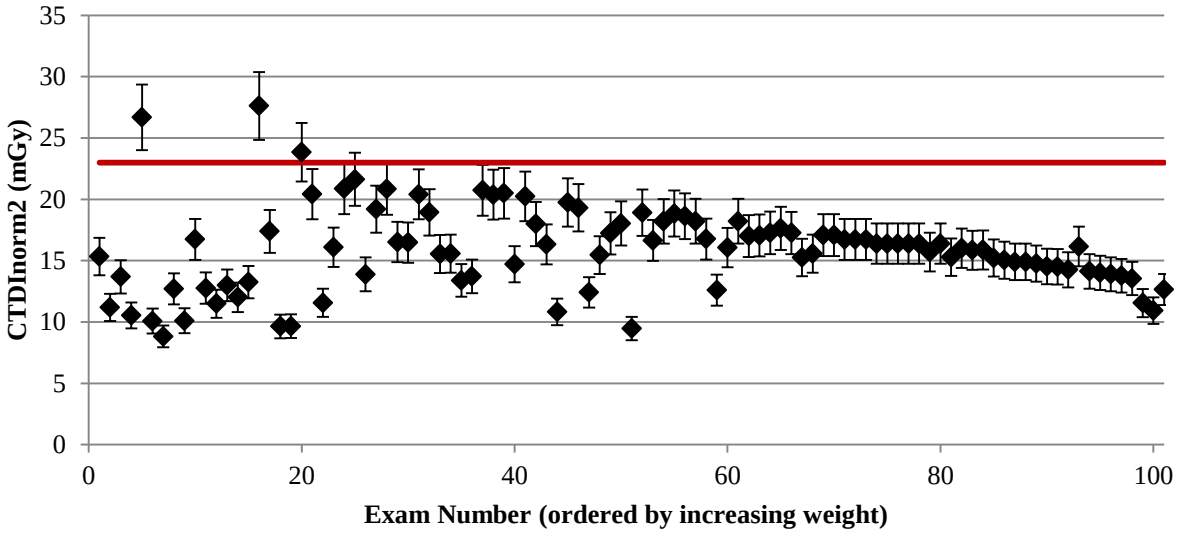

Figure 4.4.6. Renal stone $CTDI_{norm2}$ per examination number. Uncertainty is assumed as ± 10% of the calculated value.

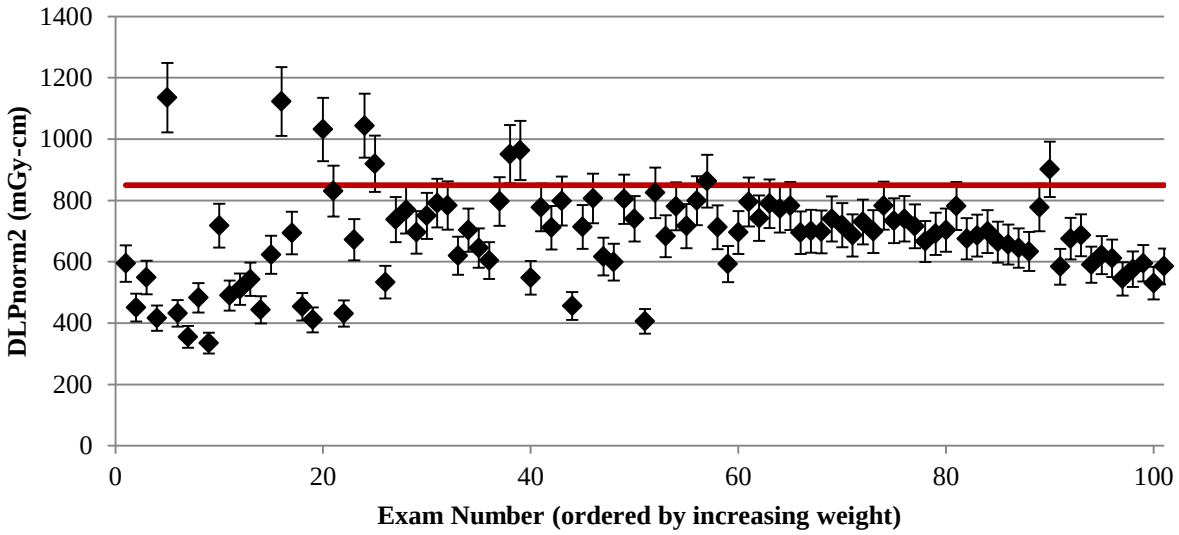

Figure 4.4.7. Renal stone DLP_{norm2} per examination number. Uncertainty is assumed as ± 10% of the calculated value.

High dose examinations based on the $CTDI_{norm2}$ threshold for the CT Renal Stone protocol are listed in Table 4.4.5. Causes of high dose are also recorded.

Table 4.4.5. Causes of high-dose ($CTDI_{norm2}$) for CT renal stone examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
5	X					
16	X					
20	X					

High dose examinations based on the DLP_{norm2} threshold for the CT Renal Stone protocol are listed in Table 4.4.6. Causes of high dose are also recorded.

Table 4.4.6. Causes of high-dose (DLP_{norm2}) for CT renal stone examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
5	X					
16	X					
20	X					
24					X	
25	X					
38					X	
39	X					
57	X					
90	X					

The second normalization expression (4.1.2.b) identified a total of nine high-dose examinations, three of which were identified for both high CTDI and high DLP. Only one of these examinations (#5) correlated with the high dose examinations as defined by the first normalization expression (4.1.2). This second transformation did identify two of the four over-scan examinations defined in the non-normalized data set; however, the other two examinations were overlooked and no new scans were identified as showing high dose caused by a technologist error.

When considering the CT Abdomen and Pelvis for Renal Stone cohort, normalization of data did not enhance the identification of high-dose examinations. Both normalization transformations excluded examinations from the high-dose categorization that were identified as

such in the non-normalized data. Both normalization functions did draw attention to examination #5, but a review of the examination was not conclusive in identifying the cause for the high dose.

4.5. CT ANGIOGRAPHY CHEST FOR PULMONARY EMBOLISM

NON-NORMALIZED DATA

CTDI data is graphed in Figure 4.5.1. Examinations were numbered in order of increasing patient weight, which is why the CTDI values trend upward until they reach the preset maximum CTDI of 24 mGy. The high dose threshold (red line) is set at 25 mGy, which is just above the apparent upper limit for the data set. This threshold clearly excludes at least one smaller patient (#9) with a high CTDI compared to patients of similar weight.

DLP data is graphed in Figure 4.5.2. Examination numbers correspond with the same patients as in Figure 4.2.1. The high dose threshold for this dose parameter was set at 900 mGy-cm since the data appears to reach a plateau just below this level. Incidentally, this is also very near to a value of 30% above the mean (917 mGy-cm). A threshold of 2s above the mean (348 mGy-cm) was also given consideration as a potential threshold values, but in this case the value seemed to exclude apparent outliers from the high dose criteria.

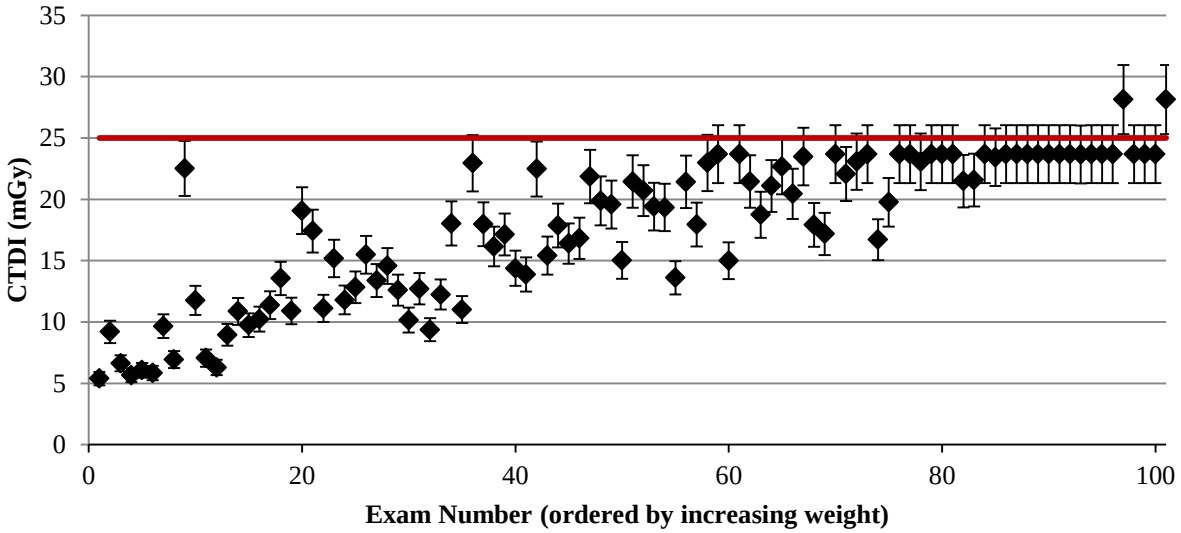

Figure 4.5.1. PE CTDI per examination number. Uncertainty is assumed as ± 10% of the measured value.

Figure 4.5.2. PE DLP per Exam Number

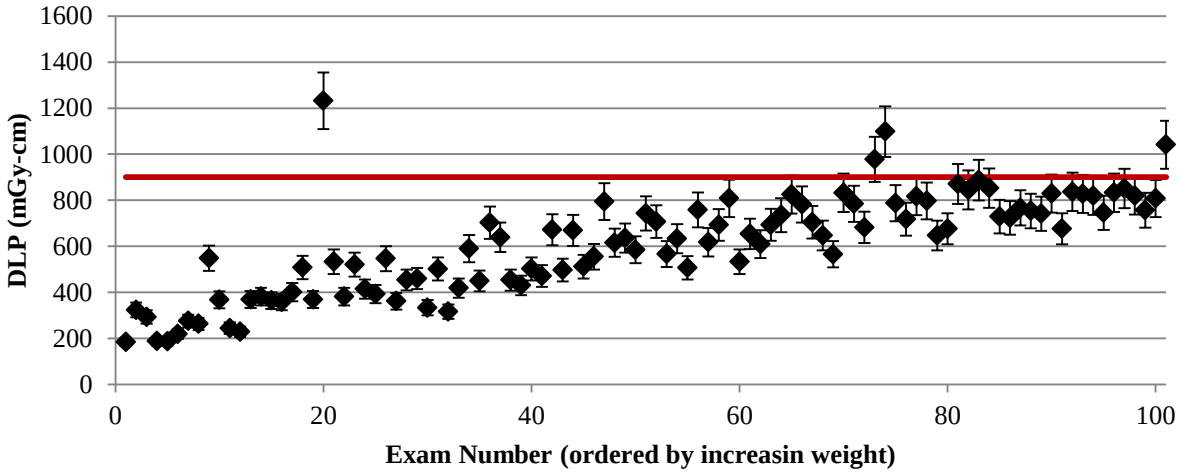

Figure 4.5.2. PE DLP per examination number. Uncertainty is assumed as ± 10% of the measured value.

High dose examinations based on the CTDI threshold for CT Angiography for PE are listed in Table 4.5.1. Causes of high dose are also recorded.

Table 4.5.1. Causes of high-dose (CTDI) for CT PE examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
97		X		X		
100		X		X		

High dose examinations based on the CTDI threshold for CT Angiography for PE are listed in Table 4.5.2. Causes of high dose are also recorded.

Table 4.5.2. Causes of high-dose (DLP) for CT PE examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
20			X			
73					X	
74			X			
100		X		X		

Two examinations exceeded the CT PE CTDI threshold, one of which also exceeded the DLP threshold (# 100). Three additional examinations are identified as being high-dose based on the DLP threshold. Both examinations exceeding the CTDI threshold were the result of the technologist manually overriding the preset technique, presumably in an effort to minimize image noise with especially large patients. While these changes did not reduce image noise compared to patients of similar size these studies were not categorized as demonstrating a technologist error.

A total of 4% of reviewed examinations (4 of 100) exceeded the DLP high-dose threshold. Two were the result of repeated series, one was the result of over-scan, and the last was a result of increased kVp, presumably the effort of the technologist attempting to maintain image quality for an especially large patient. The reason for repeated series in examinations #20 and #74 was not apparent, but a technologist error cannot be excluded. In both cases the DLP was reported as approximately double the average of the cohort. A maximum of 3% (3 of 100) of

all scans analyzed showed evidence of high-dose caused by some circumstance that might have been prevented by the technologist.

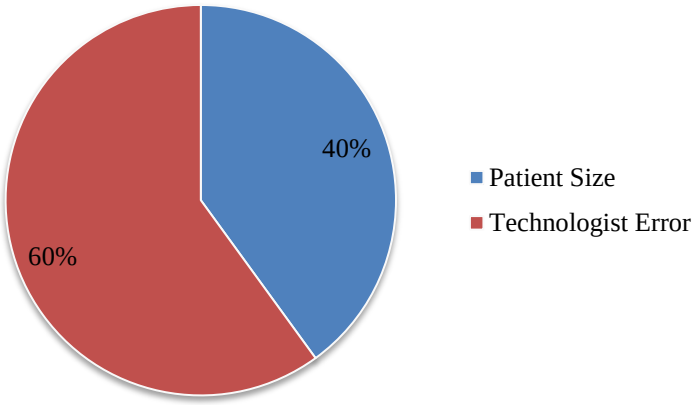

Figure 4.5.3. Causes of high-dose CT PE examinations. Technologist errors included: over-scan and repeated series.

NORMALIZED DATA: EQUATION 4.1.2

$CTDI_{norm}$ data for CT PE is graphed in Figure 4.5.4. The high dose threshold (red line) is set at the apparent upper limit of the data (40 mGy), which is equal to a value of the 2s above the mean. A threshold equal to 30% above the mean was also given consideration (27 mGy), but this value would have identified nearly 20% of all examinations as high-dose. The normalization function increased the mean from 18 mGy to 21 mGy and increased the standard deviation from 5.9 mGy to 9.5 mGy.

DLP_{norm} data for CT PE is graphed in Figure 4.5.5. The high dose threshold (red line) is set at 1350 mGy, which is equal to a value of 2s above the mean. A threshold of 30% above the mean was also considered (920 mGy-cm) but this value identified nearly half of all examinations as high dose. The normalization function increased the mean from 610 mGy-cm to 700 mGy-cm and increased the standard deviation from 210 mGy-cm to 32o mGy-cm.

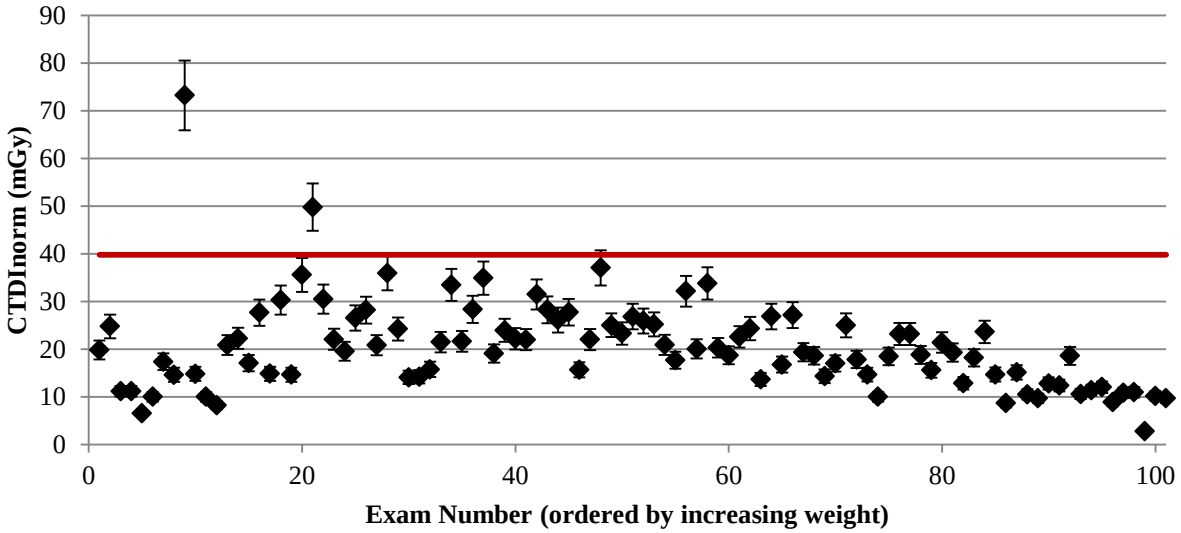

Figure 4.5.4. PE $CTDI_{norm}$ per examination number. Uncertainty is assumed as ± 10% of the calculated value.

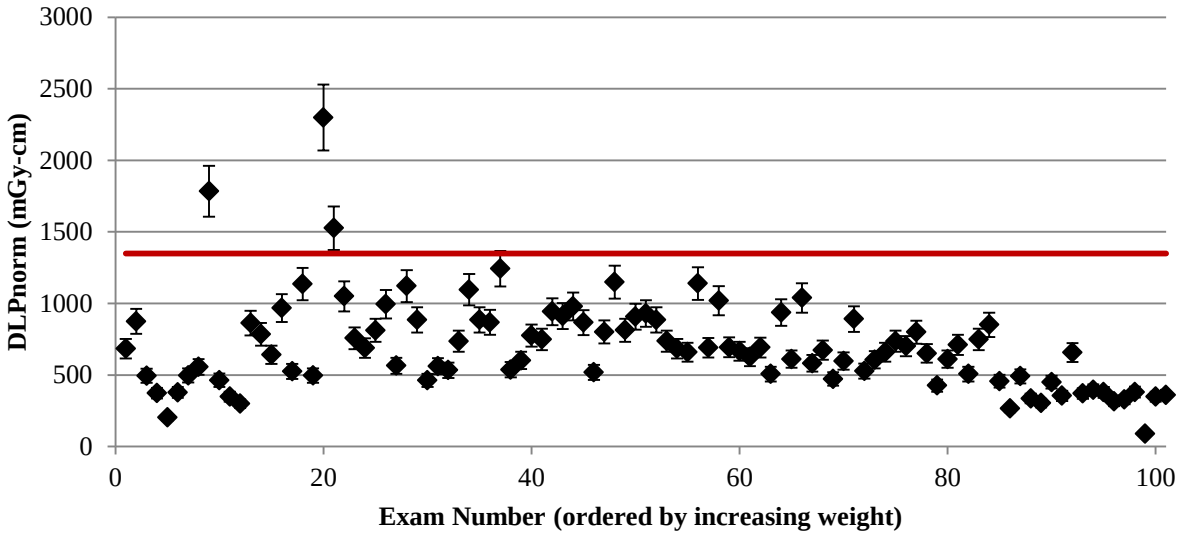

Figure 4.5.5. PE DLP_{norm} per examination number. Uncertainty is assumed as ± 10% of the calculated value.

High dose examinations based on the $CTDI_{norm}$ threshold for CT Angiography for PE are listed in Table 4.5.3. Causes of high dose are also recorded.

Table 4.5.3. Causes of high-dose ($CTDI_{norm}$) for CT PE examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
9						X
21	X					

High dose examinations based on the DLP_{norm} threshold for CT Angiography for PE are listed in Table 4.5.4. Causes of high dose are also recorded.

Table 4.5.4. Causes of high-dose (DLP_{norm}) for CT PE examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
9						X
20			X			
21	X					

Transformation of the data using expression 4.1.2 identified three high dose examinations, two of which exceeded both the $CTDI_{norm}$ and DLP_{norm} high-dose threshold. One examination was the result of repeated series, one showed no error, and one examination (#9) showed both a high $CTDI_{norm}$ and high DLP_{norm} as a result of surgically implanted metallic supports in the patient's thoracic spine. This hardware must have substantially changed the attenuation properties of the lateral localizer image therefore the scanner assigned a higher than expected dose given the patients weight.

One of these cases (#20) was also identified in the non-normalized data due to repeated Examination series. The other examination with repeated series (#74) was not identified as being high-dose in this normalization process. This normalization procedure did draw attention to one examination that might have been overlooked in the non-normalized data (#9), but otherwise no new examinations were identified as being high-dose caused by technologist decisions.

NORMALIZED DATA: EQUATION 4.1.2.b

$CTDI_{norm2}$ data for CT PE is graphed in Figure 4.5.6. This data transformation has a lower standard deviation than previous data sets. The high dose threshold (red line) was set to the apparent upper limit of the data at 26 mGy, which is also equal to a value of 2s above the mean.

DLP_{norm2} data for CT PE is graphed in Figure 4.5.7. The high dose threshold (red line) is set at 950 mGy-cm which is slightly beyond the apparent upper limit of the data and is equal to a value of 2s above the mean. The normalization function had the same effect on DLP as it did on CTDI; standard deviation decreased from 210 mGy-cm to 170 mGy-cm while the mean remained virtually unchanged (610 mGy-cm compared to 620 mGy-cm).

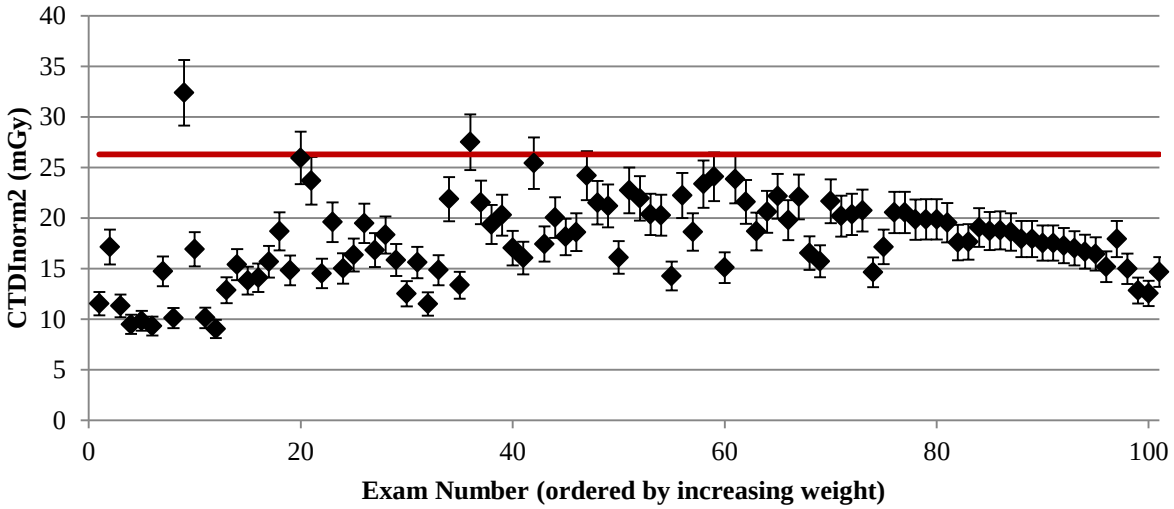

Figure 4.5.6. PE $CTDI_{norm2}$ per examination number. Uncertainty is assumed as ± 10% of the calculated value.

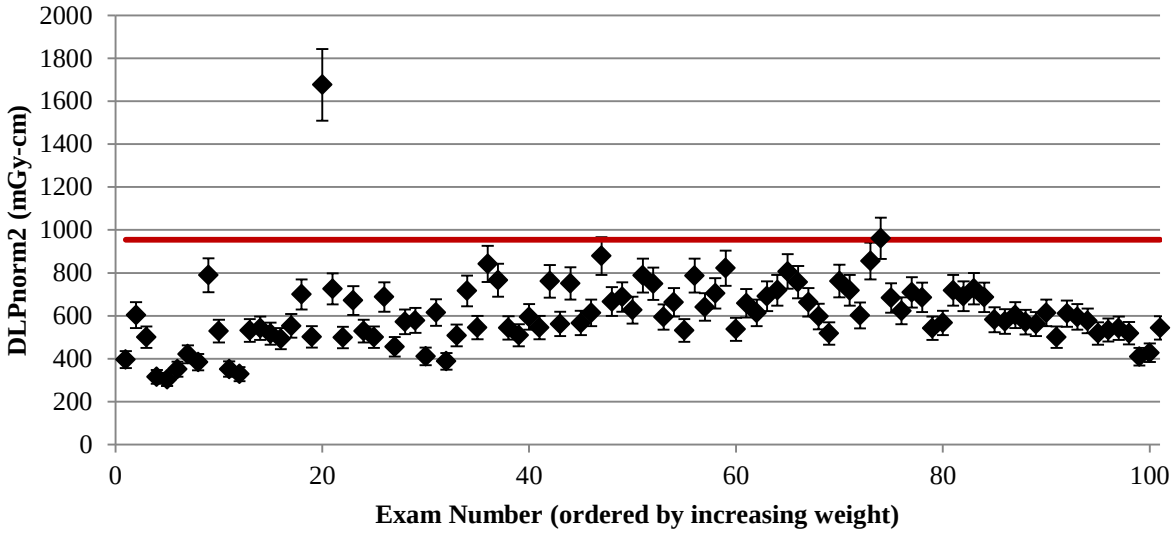

Figure 4.5.7. PE DLP_{norm2} per examination number. Uncertainty is assumed as ± 10% of the calculated value.

High dose examinations based on the $CTDI_{norm2}$ threshold for CT Angiography for PE are listed in Table 4.5.5. Causes of high dose are also recorded.

Table 4.5.5. Causes of high-dose ($CTDI_{norm2}$) for CT PE examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
9						X
36	X					

High dose examinations based on the DLP_{norm2} threshold for CT Angiography for PE are listed in Table 4.5.6. Causes of high dose are also recorded.

Table 4.5.6. Causes of high-dose (DLP_{norm2}) for CT PE examinations.

Examination Number	No Cause	Large Patient	Repeat Series	mA/kVp Change	Over-scan	Other
20			X			
74			X			

The second normalization expression (4.1.2.b) identified a total of four high-dose examinations, none of which were identified for both high CTDI and high DLP. Two of these

examinations (#9 and #20) correlated with the high dose examinations as defined by the first normalization expression (4.1.2). Examinations #20 and #74 were also identified as high-dose in the non-normalized data, both of which were attributable to repeated series. Concerning CTDI, this normalization transformation had the benefit of identifying one examination that was genuinely unusual (#9) while including only a single examination (#36) that showed no evidence of error or intervention. Concerning DLP, the transformation of the data identified two high-dose examinations caused by technologist decisions without also including examinations showing no reason for meeting the high-dose criteria.

4.6. SUMMARY OF RESULTS

A summary of dose information for non-normalized data is provided in Table 4.6.1. These values are above those published by Columbia University but still in compliance with ACR requirements.

Table 4.6.1. Average examination data and high dose thresholds

Examination Type	Mean CTDI (mGy)	Mean DLP (mGy-cm)	High-Dose CTDI (mGy)	High-Dose DLP (mGy-cm)
CT Adult Head	69.4	1170	75	1200
CT Pediatric Head	32.2	517	35	500
CT for Renal Stone	15.8	686	20	850
CT Angiography for PE	17.9	613	25	900

An overview of high-dose quantification and assessment is provided in Table 4.6.2. Data encompasses normalized and non-normalized data for both CTDI and DLP.

Table 4.6.2. High-dose quantification and assessment. non-n = non-normalized data; norm = based on data normalized with expression 4.1.2; norm2 = based on data normalized with expression 4.1.2.b. *"Oversights"* refers to examinations that should have been identified as high-dose but were not.

Examination Type	Total High-Dose Examinations		Tech. Error		No Tech. Error		Oversights	
CT Adult Head	non-n	12	non-n	4	non-n	8	non-n	--
CT Pediatric Head	non-n	36	non-n	7	non-n	29	non-n	--
CT for Renal Stone	non-n	13	non-n	4	non-n	9	non-n	1
	norm	5	norm	0	norm	5	norm	4
	norm2	9	norm2	2	norm2	7	norm2	2
CT Angiography for PE	non-n	6	non-n	3	non-n	3	non-n	1
	norm	3	norm	0	norm	3	norm	2
	norm2	4	norm2	2	norm2	2	norm2	1

HYPOTHESES

Concerning the relationship between subject thickness and absorbed dose, the data is consistent with the null model: The linear model was demonstrated as having the best predictive value based on the AIC score.

Concerning the relationship between absorbed dose and CT image noise (standard deviation), the data supports the alternative model: The power regression model was demonstrated as having the best predictive value based on the AIC score.

Concerning the normalization of patient dose, the data is consistent with the null model: Normalizing patient dose did not increase the total number of high-dose examinations demonstrating a correctable technologist error. For CT Renal Stone and CT PE examinations, non-normalized data was effective in identifying 7 high-dose cases with technologist errors. Normalization with expression 4.1.2 showed 0 cases and expression 4.1.2b identified 4 cases.

Concerning the causes of over-exposure, non-normalized data demonstrated that 27% (18 of 67) of all high-dose examinations were caused by correctable technologist decisions. This represented 4.5% of all examinations studied. Using Wilson's Estimators (expressions 3.4.1 and 3.4.2), the mean technologist error rate is calculated as 4.9% ± 2.1% for examinations

considered. For CT Adult Head the mean technologist error rate is calculated as 5.8% ± 4.5%. For CT Pediatric Head the mean technologist error rate is calculated as 8.7% ±5.4%. For CT Renal Stone the mean technologist error rate is calculated as 5.8% ± 4.5%. For CT Pulmonary Embolism the mean technologist error rate is calculated as 4.8% ± 4.1%.

CHAPTER 5: CONCLUSIONS

5.1. SUMMARY

A linear relationship between subject thickness and the corresponding CTDI was verified when using the CT scanners automatic mA-modulating function, although non-linear models could also have been used to describe these relationships. A power-regression was found to define the relationship between subject thickness and image noise, which was represented as the standard deviation of CT numbers in the image. The relationships between subject thickness, dose, and image noise were used to define two normalization functions which were then applied to the dose data for CT renal stone and CT PE examinations. The normalization transformations drew attention to two additional examinations while missing nine other examinations that had demonstrated verifiable technologist errors in the non-normalized data. For this reason normalization based on patient weight and/or image noise is not recommendation as an alternative to evaluating non-normalized data. Transformation of DLP data might be improved by normalizing to the patients' body mass index (BMI) as this measure of patient size also accounts for the patient height.

High-dose thresholds were explored through various mechanisms, but for non-normalized data a threshold set at the apparent upper limit the protocol (but below obvious outliers) was most effective at defining high-dose examinations caused by technologist errors. Thresholds equal to 30% above the mean and two standard deviations above the mean were not effective in identifying high-dose examinations in the non-normalized data. Setting the threshold based solely in ACR references levels is not recommended as this method would have excluded several examinations that did in fact show evidence of errors or other circumstances resulting in a higher dose.

Overall, 67 of 400 examinations were identified as meeting the high dose criteria for non-normalized data. Within this cohort, 27% (18 of 67) were caused by correctable technologist decisions. This represented 4.5% of all examinations studied.

5.2. FUTURE WORK

Future studies on the role of the technologist in patient dose optimization should attempt to replicate the high-dose thresholds in this cohort using different data sets. Verifying these thresholds would be especially valuable since The Joint Commission (TJC) does require collection and assessment of all examinations that exceed pre-determined dose limits. Expanding the study to include different technologists, different facilities, and different scanners would help to define the extent to which these thresholds are applicable throughout an organization.

Efforts to define an effective normalization function should continue. As an example, 6 of 13 high-dose renal stone examinations showed no verifiable error or cause whatsoever. Additionally, it is possible that some smaller patients are receiving excessive dose without actually exceeding the high-dose threshold. A well-designed normalization scheme should be able to draw attention to examinations that are currently being overlooked while also excluding examinations that are not associated with a verifiable error. This might be accomplished by normalizing to BMI and defining the normalizing function with phantoms that are more reflective of the sizes and shapes of human bodies.

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APPENDIX A: DATA SETS

CT ADULT HEAD WITHOUT CONTRAST

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
1	96	5.5	72.13	1017.93
2	94	5.2	67.42	1163.35
3	96	6.1	67.42	1409.06
4	96	4.4	68.95	1163.35
5	120	6.5	67.42	1163.35
6	85	5.2	67.65	1163.35
7	70	6.2	70.56	1452.18
8	72	5.5	67.42	1163.35
9	64	5.5	67.42	1017.93
10	58	5.3	67.42	1163.35
11	71	4.9	67.42	1163.35
12	71	5.1	71.60	1454.19
13	49	5.0	67.42	1017.93
14	103	5.7	67.42	1308.76
15	69	4.5	67.42	1163.35
16	113	6.7	68.76	1163.35
17	70	5.8	72.49	1219.51
18	51	6.5	67.42	1163.35
19	144	8.1	72.62	1163.35
20	64	4.7	72.01	1163.35
21	68	5.3	67.42	1163.35
22	93	5.3	67.42	1017.93
23	90	7.5	67.42	1163.35
24	115	5.3	67.42	1163.35
25	103	9.3	67.42	1163.35
26	92	6.1	70.99	1163.35
27	108	6.4	70.67	1177.39
28	71	5.0	72.64	1017.93
29	61	3.9	71.92	1017.93
30	74	5.3	71.37	1163.35
31	85	6.7	69.35	1163.35
32	79	5.1	72.71	1454.19
33	100	6.8	70.67	1613.64
34	153	7.6	67.42	1163.35
35	50	4.0	72.01	1017.93
36	80	4.8	67.42	1163.35
37	71	5.5	67.42	1163.35

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
38	88	4.6	70.67	1773.11
39	70	5.0	67.42	1163.35
40	53	4.9	72.24	1163.35
41	100	6.0	67.42	1163.35
42	62	5.9	67.87	1163.35
43	88	6.4	67.42	1163.35
44	64	5.3	71.60	1163.35
45	48	5.3	76.22	1371.95
46	88	4.2	67.42	1163.35
47	110	5.7	67.42	1163.35
48	50	5.2	67.87	1163.35
49	86*	5.5	67.42	1017.93
50	110	6.1	71.37	1163.35
51	88	4.7	71.37	1163.35
52	88	6.1	67.42	1163.35
53	110	7.8	68.95	1017.95
54	86*	5.2	67.42	1017.95
55	82.9	5.0	68.54	1163.35
56	102	6.2	67.42	1163.35
57	105	6.2	69.71	1017.95
58	102	4.2	71.25	1163.35
59	60	4.0	72.71	1163.35
60	91	6.0	70.99	1163.35
61	120	4.3	70.06	1163.35
62	73	5.3	68.32	1163.35
63	71	5.2	67.42	1163.35
64	170	6.7	68.76	1163.35
65	86	4.4	74.94	1219.51
66	86*	7.0	68.95	1163.35
67	100	6.5	67.87	1163.35
68	122	5.5	72.01	1163.35
69	86*	4.5	69.53	1163.35
70	86*	4.4	67.65	1017.93
71	106	6.0	71.13	1163.35
72	101	5.5	67.42	1017.93
73	49	4.4	67.42	1017.93
74	79	5.2	70.56	1163.35
75	98	5.5	69.35	1163.35
76	101	5.5	67.42	1163.35
77	90	4.3	70.23	1163.35
78	70	4.6	67.42	1017.93

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
79	73	4.7	70.85	1017.93
80	86*	5.6	67.42	1163.35
81	62	5.9	67.42	1163.35
82	78	4.6	69.35	1017.93
83	40	3.4	69.35	1017.93
84	85	5.6	67.87	1163.35
85	56	4.2	71.25	1163.35
86	95	6.6	69.53	1163.35
87	86*	5.5	68.32	1163.35
88	80	6.1	68.76	1163.35
89	73	5.6	67.42	1163.35
90	95	4.6	70.56	1163.35
91	94.2	6.0	67.42	1017.93
92	86*	6.9	88.34	1524.37
93	71	5.0	67.42	1163.35
94	80	6	68.32	1163.35
95	60	5.1	67.42	1163.35
96	116	6.0	72.71	1308.77
97	107	5.7	68.32	1163.35
98	78	4.3	67.42	1017.93
99	109	5.7	71.49	1163.35
100	90	5.6	68.95	1163.35

**Indicates no patient weight was available. Listed value is the average of all other patients.*

CT PEDIATRIC HEAD WITHOUT CONTRAST

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
1	2.7	3.7	26.17	276.8
2	3.3	4.2	27.61	332.16
3	2.8	5.1	23.97	719.67
4	4.6	3.5	27.12	387.51
5	6.1	4.4	27.67	387.51
6	6.8	3.9	27.68	387.52
7	4.4	3.4	25.66	332.16
8	3.5	3.9	26.09	332.16
9	3.2	3.9	31.54	392.81
10	3.4	4.5	17.90	215.42
11	3.6	4.0	27.80	333.60
12	7.5	2.8	73.44	1174.97

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
13	6.2	3.7	27.53	332.16
14	5.0	3.4	27.44	332.16
15	8.0	4.9	27.68	387.51
16	5.0	4.1	27.67	332.16
17	8.3	7.3	27.17	830.38
18	2.4	2.6	26.97	276.8
19	6.8	4.5	26.97	387.51
20	2.6	2.2	27.44	498.24
21	6.7	4..6	27.68	387.52
22	8.0	4.9	27.65	332.16
23	5.0*	5.1	26.54	387.51
24	3.6	4.9	25.57	332.16
25	5.7	4.2	27.53	332.16
26	6.7	4.0	26.67	387.51
27	6.4	4.0	31.35	471.76
28	10	8.2	27.12	498.23
29	11	6.2	27.55	498.23
30	12	4.1	31.77	471.76
31	11	5.5	27.65	387.51
32	9.2	4.4	29.03	845.79
33	7.9	5.3	28.57	400.99
34	10	5.2	27.64	387.51
35	10	5.0	32.73	458.28
36	13	3.9	41.65	606.54
37	9.5	3.6	27.64	387.51
38	12	4.8	31.13	471.76
39	12	4.4	32.70	625.80
40	10	5.4	25.48	387.51
41	12	5.5	27.67	387.51
42	7.5	4.9	27.68	387.51
43	11	4.3	25.66	332.16
44	9.8	5.7	27.68	775.04
45	10*	4.4	27.68	442.88
46	9.5	5.1	27.68	442.88
47	13	4.9	27.64	387.51
48	11	3.9	33.69	471.76
49	11	3.0	67.05	813.46
50	11*	3.6	31.57	606.55
51	11*	4.5	31.13	471.76
52	10	3.9	33.51	471.76
53	12	4.7	33.13	1078.3

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
54	14	5.0	32.70	606.54
55	14*	5.8	33.13	471.76
56	17	4.9	33.32	606.55
57	14	5.2	33.18	471.76
58	14*	5.9	30.18	640.24
59	15	5.6	33.54	539.15
60	14.8	4.5	33.70	471.76
61	14	4.8	33.70	471.76
62	11	4.4	33.51	471.76
63	13	5.3	33.70	539.15
64	12	5.4	33.18	471.76
65	12	4.0	33.70	741.30
66	11	3.8	33.54	471.76
67	13	5.4	31.66	471.76
68	15	5.3	33.70	673.94
69	13*	4.4	33.66	471.76
70	11	4.1	33.70	539.14
71	13	5.1	33.70	539.15
72	12	8.1	33.23	606.50
73	13	5.2	32.76	471.76
74	14	3.5	33.23	539.15
75	14*	5.3	31.24	471.76
76	14*	5.7	33.70	539.14
77	17	5.4	33.70	606.55
78	13	5.4	33.70	471.76
79	16	6.0	33.70	673.94
80	11	5.3	33.37	471.76
81	15	4.4	33.13	471.76
82	15*	6.4	33.37	648.67
83	18	4.2	33.70	606.54
84	14	5.1	33.70	965.43
85	16	5.6	33.6	1013.02
86	25	4.1	33.69	539.15
87	17	6.1	33.18	471.76
88	16*	7.4	31.57	134.79
89	16	4.9	73.71	1179.39
90	16	4.8	33.69	404.36
91	22	7.1	31.57	673.94
92	16	4.9	33.54	471.76
93	15	4.1	33.18	471.76
94	15	5.2	33.70	471.75

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
95	13	4.6	38.51	702.82
96	16*	4.6	33.70	539.15
97	16	5.2	29.89	539.15
98	17*	5.2	32.90	471.76
99	16	5.0	33.33	539.15
100	18	6.8	33.70	539.15

**Indicates no patient weight was available. Listed value was estimated based on weight of patients of similar age.*

CT ABDOMEN AND PELVIS WITHOUT CONTRAST FOR RENAL STONE

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
1	40	18	7.05	273.25
2	43	22	5.53	222.76
3	47	14	7.39	296.55
4	47	18	5.69	224.79
5	50	18	15.34	652.37
6	50*	21	5.79	248.20
7	50	20	5.07	204.03
8	52	17	7.59	288.49
9	56	23	6.05	215.49
10	56	31	10.77	462.01
11	57	18	8.36	321.06
12	57	21	7.53	334.41
13	57	20	8.51	355.58
14	58	17	8.01	295.52
15	58	19	8.83	415.02
16	59	22	18.73	761.43
17	59	14	11.79	470.38
18	65	25	7.20	338.59
19	68	23	7.55	320.84
20	68	21	18.63	806.30
21	70*	14	16.43	668.04
22	72	15	9.57	356.89
23	72	25	13.32	556.32
24	72	24	17.27	863.91
25	72.2	17	17.95	763.16
26	73	19	11.65	447.45

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
27	73	25	16.11	618.70
28	75	18	17.96	662.52
29	75*	17	14.24	600.03
30	76	16	14.39	654.93
31	77	15	18.06	700.13
32	77	14	16.75	693.40
33	77	17	13.75	548.50
34	77	16	13.78	622.05
35	77	23	11.85	570.43
36	77	15	12.14	534.44
37	79	31	18.84	723.34
38	80*	26	18.74	874.31
39	80	25	18.84	885.82
40	80*	18	13.52	503.77
41	81	23	18.84	723.34
42	81	20	16.75	661.97
43	82	18	15.38	752.21
44	82	17	10.19	429.31
45	83	18	18.84	680.96
46	84	16	18.64	778.48
47	84	18	11.99	595.47
48	84	25	14.92	578.41
49	84	20	16.64	776.22
50	84	20	17.41	714.33
51	85	24	9.35	400.95
52	86	24	18.69	815.64
53	86	24	16.46	675.41
54	86	19	17.99	771.88
55	87	22	18.84	716.28
56	88	18	18.84	808.11
57	90	26	18.84	892.88
58	90*	18	17.34	737.40
59	90	18	13.03	612.70
60	90*	19	16.62	719.31
61	90	16	18.84	822.24
62	91	15	17.79	776.36
63	91	17	17.84	825.66
64	91	20	18.06	808.65
65	93	29	18.84	836.37
66	95	24	18.84	758.66
67	95	21	16.65	763.98

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
68	95*	17	17.00	761.57
69	95.9	26	18.84	815.18
70	96	23	18.84	793.98
71	98	28	18.84	772.79
72	98	28	18.84	822.24
73	98	20	18.84	786.92
74	100	25	18.84	899.95
75	100*	32	18.84	843.43
76	100	52	18.84	850.50
77	100	25	18.84	822.24
78	100	23	18.84	765.73
79	100	31	18.05	794.45
80	100*	27	18.84	808.11
81	101	19	17.74	907.43
82	102	31	18.77	791.17
83	103	36	18.76	811.62
84	103	25	18.79	827.23
85	106	35	18.54	809.03
86	109	26	18.84	822.24
87	110*	25	18.84	815.18
88	110*	33	18.84	801.05
89	111	29	18.84	991.78
90	111	28	18.54	1149.74
91	113	44	18.84	758.66
92	115*	25	18.84	892.88
93	116	18	21.53	915.48
94	116	31	18.84	786.92
95	117	32	18.84	836.37
96	118	29	18.84	829.30
97	119	30	18.84	744.53
98	121	36	18.84	801.05
99	142	46	18.84	970.59
100	163	32	23.68	1095.84

**Indicates no patient weight was available. Listed value was estimated based on the CTDI and standard deviation.*

CT ANGIOGRAPHY FOR PULMONARY EMBOLISM

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
1	47	23	5.38	185.04
2	54	26	9.19	323.95
3	59	34	6.63	292.91
4	60	30	5.65	188.03
5	62	45	6.06	187.41
6	63	32	5.83	219.53
7	66	30	9.65	275.84
8	69	26	6.93	263.43
9	70	19	22.52	548.69
10	70	37	11.76	367.46
11	70	34	7.05	244.82
12	70	36	6.29	228.59
13	70	24	8.95	369.44
14	71	26	10.86	382.23
15	71	29	9.74	364.56
16	73	21	10.23	357.88
17	73	35	11.36	401.29
18	73	24	13.55	507.53
19	74	34	10.9	368.76
20	74	27	19.07	1232.03
21	74	20	17.41	533.68
22	77	20	11.10	382.18
23	78	31	15.18	520.34
24	79	28	11.79	414.79
25	79	24	12.83	392.95
26	80*	26	15.48	546.55
27	80	29	13.37	361.98
28	80	21	14.57	454.31
29	80	25	12.59	459.66
30	81.7	31	10.15	333.16
31	82	36	12.71	501.53
32	82	27	9.37	316.38
33	83	26	12.24	418.96
34	83	25	18.03	590.52
35	83	24	11.01	449.43
36	84	33	22.95	702.4
37	84	24	17.97	638.94
38	84	34	16.15	453.39
39	85	30	17.13	430.3

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
40	85	28	14.38	502.15
41	87	27	13.87	470.99
42	89	29	22.47	672.47
43	89	24	15.41	497.08
44	89.7	28	17.87	669.29
45	91	25	16.39	511.77
46	91	38	16.81	555.07
47	91	36	21.86	794.52
48	93	23	19.87	615.77
49	93	30	19.58	635.62
50	94	26	15.03	585.12
51	95*	30	21.45	743.47
52	95	30	20.71	707.09
53	96	29	19.41	566.67
54	96	33	19.33	632.9
55	96	29	13.60	507.07
56	97	26	21.42	758.51
57	97	32	17.94	617.38
58	99	26	22.97	692.82
59	99	38	23.68	808.47
60	100	29	15.00	533.52
61	100	35	23.68	653.98
62	100	31	21.45	609.64
63	101	42	18.74	693.56
64	103	28	21.09	735.67
65	103	41	22.67	825.26
66	104	27	20.44	781.87
67	107	37	23.48	704.55
68	109	31	17.91	646.6
69	110	36	17.18	565.79
70	110	40	23.68	832.37
71	110	29	22.06	785.24
72	114	37	23.07	682.18
73	115	43	23.68	977.45
74	115	44	16.71	1098.21
75	116	32	19.76	787.29
76	116	31	23.68	717.95
77	116	31	23.68	816.94
78	117	35	23.06	797.23
79	120	40	23.68	646.91
80	120	32	23.68	675.85

Examination Number	Patient Weight (kg)	Standard Deviation	CTDI (mGy)	DLP (mGy-cm)
81	122	34	23.68	870.73
82	123	42	21.48	844.94
83	123	33	21.56	887.46
84	125	29	23.68	852.53
85	126	40	23.43	728.52
86	127	58	23.68	723.52
87	128	39	23.68	766.97
88	133	49	23.68	753.48
89	133	52	23.68	741.54
90	136	42	23.68	828.94
91	136	43	23.68	676.01
92	138	32	23.68	836.36
93	140	47	23.65	827.59
94	143	44	23.68	819.26
95	145	42	23.68	745.9
96	157	49	23.68	832.65
97	158	48	28.13	851.74
98	159	42	23.68	819.5
99	186	99	23.68	756.79
100	193	45	28.13	1041.22

**Indicates no patient weight was available. Listed value was estimated based on the CTDI and standard deviation.*