Accuracy of Effective Dose Estimation Using Single and Double Badges and an Evaluation of Organ Dose and Image Quality in Thoracic MDCT Scans Through a Comparison of Bismuth Shields and a Global Reduction in Tube Current

by

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Date:_______________________

Approved:

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Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Medical Physics in the Graduate School of Duke University

2012
ABSTRACT

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Abstract

Purpose: (1) To benchmark the accuracy of effective dose equivalent (EDE) of the single- and double-badge methods (NRC 2002-06) using the commercially available radiation monitors in clinical settings, (2) to study the transmission properties of various shielding materials, (3) to evaluate the accuracy of film badge readings compared to a calibrated ion chamber, (4) to benchmark the accuracy of effective dose (ED) of the single- and double-badge methods (NRC 2002-06) using the MOSFET method, and (5) to investigate the organ dose and image quality in a thoracic MDCT scan under the following conditions: (a) tube current modulation (TCM) without a Bismuth shield, (b) TCM with a Bismuth shield, and (c) manually reduced tube current (RTC) with no Bismuth shield.

Methods and Materials: (Project 1): Radiation workers in interventional radiology and cardiac catheterization laboratory were provided with two monitors and asked to place one at the collar and the other underneath the lead apron. Two commercial radiation monitor vendors were used for the study; both vendors were accredited by the National Voluntary Laboratory Accreditation Program (NVLAP). Effective dose equivalent (EDE) was computed by single-badge and double-badge methods based on the NRC Publication 2002-06. Data were plotted EDE1 (single badge) vs. collar reading and EDE2 (double badge) vs. collar reading. Data on EDE2 vs. collar reading were fitted by linear regression and a new equation for the EDE2\text{collar} was derived for routine clinical EDE estimation.
(Project 2): The transmission properties of lead aprons and a thyroid shield were measured using a 6-cc ion chamber and electrometer. These measurements were taken on a GE VCT (64 slice) scanner at 80, 100, and 120 kVp. The different types of lead aprons studied included lead free, lightweight lead, and fully leaded.

(Project 3): The accuracy of film badges was evaluated by comparing the reported deep dose equivalent of the film badge readings to the ion chamber readings measured during the same exposure. The measurements were made on a Philips Standard Radiography unit (Duke North, Room H1) at 80, 100, and 120 kVp. Two badges were exposed with the ion chamber per energy.

(Project 4): An adult male anthropomorphic phantom was loaded with 20 diagnostic MOSFET detectors and scanned without lead aprons using a whole body computed tomography (CT) protocol. All measurements were taken on a GE VCT (64 slice) scanner at 80, 100, 120 kVp. Two commercial film badges were placed on the phantom at the collar location and waist location. Individual organ doses in the phantom were corrected for lead apron attenuation factor and ED was computed using ICRP 103 tissue weighting factors. The single badge conversion coefficient (CC) was determined for each energy by taking the ratio of the ED to collar badge reading. The reported deep dose equivalent for the collar badge was plotted against the MOSFET effective dose and a new equation for \( ED_{\text{collar}} \) was derived.

(Project 5): Organ dose was measured with MOSFETs using an adult female anthropomorphic phantom; the phantom was scanned with pulmonary embolus protocol. All measurements were performed with a 64-slice scanner at
120 kVp. The reference exposure and reduced exposure (with 4-ply Bi shield) was measured with an ion chamber located at the level of the breast. The tube current was reduced by normalizing the reference tube current to the ratio of the reduced exposure to the reference exposure. Image quality was measured using a high contrast insert placed in the lung. Regions of interest (ROIs) were drawn in the breast, lung, and heart to measure HU change and noise. ROIs were drawn in the lung and high contrast insert to measure signal-to-noise ratio (SNR) and percent contrast (%Contrast).

**Results:** (Project 1): From the data, it can be seen that EDE1 read about a factor of six greater than EDE2. The new equation for EDE2_{collar} yielded a slope of 0.06992, a y-intercept of -1.682, and a $r^2$ value of 0.9081.

(Project 2): The transmission for the fully leaded, lightweight lead aprons, and lead free apron were 3.19%, 3.71%, and 7.06% at 80 kVp; 6.58%, 8.07%, and 13.04% at 100 kVp; 7.61%, 12.05%, and 17.84% at 120 kVp, respectively. The attenuation for the thyroid shield was 3.02%, 6.35%, and 7.74% at 80, 100, and 120 kVp, respectively.

(Project 3): The average badge reading was 3.49 ± 1.01% mSv at 80 kVp; 4.80 ± 7.37% mSv at 100 kVp; 4.90 ± 14.1% mSv at 120 kVp. The dose to soft tissue measured by the ion chamber was 4.53 mSv at 80 kVp; 5.71 mSv at 100 kVp; 6.35 mSv at 120 kVp. The film badge reading differed from the ion chamber measurement by -22.8%, -15.9%, and -22.9% at 80, 100, and 120 kVp, respectively.

(Project 4): The ED and % difference between the single-badge method (NRC 2002-06) and the MOSFET method were as follows: 11.65 mSv vs. 0.50 mSv (2331%) for 80 kVp; 27.85 mSv vs. 2.14 mSv (1301%) for 100 kVp; 38.59 mSv vs. 2.65 mSv (1398%).
4.98 mSv (775%) for 120 kVp, respectively. The ED and % difference between the double-badge method (NRC 2002-06) and the MOSFET method were as follows: 4.07 mSv vs. 0.50 mSv (808%) for 80 kVp; 16.9 mSv vs. 2.14 mSv (791%) for 100 kVp; 25.4 mSv vs. 4.98 mSv (510%) for 120 kVp, respectively. The single badge conversion factors were 0.01 ± 14.8% (80 kVp), 0.02 ± 9.5% (100 kVp), and 0.04 ± 15.7% (120 kVp). The plot of collar badge reading vs. MOSFET effective dose yielded an equation with a slope of 0.0483, a y-intercept of -1.6517, and a $R^2$ value of 0.92929.

(Project 5): Organ doses (mGy) for the three scans (TCM, TCM with Bi, and RTC with no Bi) were 45.8, 27.1, and 27.8 to the breast; 51.6, 47.0, and 29.1 to the lung; and 42.1, 35.0 and 24.9 to the heart, respectively. HU increase was greatest in the TCM with Bi scan. The SNRs were 77.1, 63.7, and 59.2 and the %Contrast values were 369.5, 347.1, and 362.7 with TCM, TCM with Bi, and RTC, respectively.

**Conclusions:** (Project 1): A new EDE estimation method has been developed based on the results of two-badge system. The method would enable us to compute new EDE values knowing only the collar badge reading. Since EDE2 reads a factor of six less than EDE1, this provides a realistic advantage in regulatory compliance for interventional and cardiac catheterization personnel. Further, new EDE conversion coefficients should be developed for better assessment of EDE.

(Project 2): The fully leaded shielding materials had the lowest percent transmission. It should be noted that radiation workers are generally exposed to only scattered radiation of lower energy. Although this study did not measure
attenuation properties at lower energies, it is expected that the percentage of attenuation will only increase with lower energies.

(Project 3): The reported deep dose equivalent (DDE) underestimated the dose to soft tissue compared to the calibrated ion chamber readings. This may be due to the fact that DDE is the dose equivalent at a depth of 10 mm.

(Project 4): Current regulatory ED conversion coefficient (CC) with single collar badge is 0.3; for double-badge system, they are 0.04 and 1.5 for the collar and under the apron respectively. Based on our findings we recommend the current collar CC be dropped due to the overestimation of ED. Since occupational workers are exposed mainly to scattered x-rays of lower energy, a collar CC of 0.01 (80 kVp data) may be a more viable option. The double badge system seems to provide a better coefficient for the collar as 0.04; however, exposure readings under the apron are usually negligible to zero with lead aprons.

(Project 5): For thoracic CT using RTC will result in similar global reduction in organ dose; the use of Bismuth with TCM will lead to an overall decrease in organ dose and more marked dose reduction for the breast. There was a significant difference in SNR (p = 0.0003) and %Contrast (p < 0.0001) in the TCM with Bismuth scan compared to the reference scan (TCM). The RTC scan also demonstrated a significant decrease in SNR and %Contrast with p < 0.0001 for both. While the TCM scan demonstrated superior image quality, the trade-off is in the increased dose to the breast.
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1. Introduction

1.1 Overview

Radiation has been an important aspect of medical imaging beginning with the discovery of x-rays by Wilhelm Roentgen on November 8, 1985 [1]. Since the production of the first anatomical radiograph by Roentgen, the field of Radiography has expanded to include occupations, like radiologists and radiographers, and advanced imaging modalities, like fluoroscopy, mammography and computed tomography (CT) [1]. These advanced imaging modalities have reduced the numbers of exploratory surgery and have provided the ability to visualize and diagnose a large number of pathologies [1]. While these advancements have led to great gains in the medical industry, they also entail routine exposure to occupational workers [2].

According to the National Council on Radiation Protection and Measurements (NCRP), the largest group of occupationally exposed individuals in the United States is made up of persons that are directly involved with the use of ionizing radiation in the medical environment [3]. In addition, the NCRP reported that second largest fraction of collective occupational dose is received by this group [3]. In the diagnostic imaging department, fluoroscopy procedures and some special procedures, including digital subtraction angiography (DSA) and cardiac catheterization, are the major source of occupational dose [3]. During these procedures, the radiologist must be present in the examination room to operate the x-ray machine and a considerable amount of beam-on time may be required.

Dose is defined as the energy imparted to matter per unit mass from ionizing radiation [4].
where \( d\varepsilon \) is the energy imparted and \( dm \) is finite mass. The unit of dose, otherwise known as absorbed dose, is a Joule per kilogram (J/kg); one Joule per kilogram is equal to one Gray (Gy).

Occupational radiation dose is to be monitored to ensure that it is within regulatory limits. Currently, the United States Nuclear Regulatory Commission (NRC) regulations state that the annual occupational dose limit is 50 mSv, not including medical or background radiation [5]. In external dosimetry, dose is measured by a variety of different dosimeters including ionization chambers, thermoluminescent dosimeters (TLDs), metal-oxide semiconductor field-effect transistors (MOSFETS), and film. The following sections will provide an introduction to the operation of MOSFETS and film dosimeters.

### 1.2 Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET)

The use of MOSFETS as dosimeters was suggested as far back as 1974 [6]. Currently, they are used as integrating dosimeters in X- and gamma-ray exposures, producing near real-time measurements [6]. They can be used as a cumulative dosimeter by relating the voltage shift across the MOSFET to dose [7].

A schematic of a P channel MOSFET is displayed in Figure 1.1. This type is built on a negatively doped (n-type) silicon substrate [8]. The source and the drain are two terminals located on top of a positively doped (p-type) silicon area; p-type areas contain more positively charged electron holes than negatively charged electrons [7]. The third terminal, known as the gate, is built on top of an insulating layer of silicon dioxide [7].
Beneath the oxide region is a negatively doped (n-type) silicon substrate [7]. The channel region is located immediately below the oxide layer and is part of the silicon substrate [7].

![Figure 1.1: Schematic of a P Channel MOSFET](image)

When a sufficient negative voltage is applied to the gate, positively charged holes move from the silicon substrate and the source and drain regions to the oxide-silicon interface [8]. After an adequate number of holes have reached the oxide-silicon interface, a conduction channel is formed between the source and the drain, which allows for the flow of current [8]. The threshold voltage ($V_{TH}$) is defined as the voltage needed to initiate current flow [8].

Ionizing radiation produced electron-hole pairs in the silicon substrate, which move to the oxide-silicon interface where they become trapped causing a negative threshold voltage shift ($\Delta V_{TH}$) [8]. Therefore, the threshold voltage will change after each irradiation. However, the voltage shift is measured before and after exposure, and is proportional to dose allowing the MOSFET to be used as a dosimeter [8].
1.3 Film Badge

Film badges have been used to measure occupational dose in diagnostic radiology since the 1940s [9]. Film badge detectors consist of a piece of personal monitoring film that is sealed in a packet to prevent light-induced exposure [10]; the film packet is placed in a plastic holder that allows for the dosimeter to be worn on the body. To stimulate different tissue depths, the radiation will penetrate five different filters before encountering the film packet; the filters contained in the plastic holder include open window, aluminum, copper, lead/tin, and plastic [10]. Radiation dose is reported after the manufacturer analyzes the film badges. The minimum reportable dose for the film badge is approximately 0.10 mSv [10].

There are many advantages to film badge dosimetry including an inexpensive cost, ease of usage, and a permanent record of exposure history. However, film badges are not reusable and can only be worn for finite periods of time [9].
2. Comparison Between Double-Badge and Single-Badge Personal Dosimetry

2.1 Introduction

Fluoroscopy procedures are the largest source of occupational exposure in medicine [11]. It is therefore important to monitor whole-body radiation dose to staff involved in these procedures, which is generally done through the use of film badge dosimeters. The National Council on Radiation Protection and Measurements (NCRP) has reported that occupational exposure is not uniform across the body due to the use of protective shielding devices [12]. In order to estimate the risk from a non-uniform exposure, the International Commission on Radiological Protection (ICRP) has developed the concept of effective dose equivalent by relating the non-uniform exposure to an equivalent whole body exposure [13].

Film badge dosimetry may be either single or double; single badge dosimetry involves one film badge at the collar, while double badge dosimetry involves placing one film badge at the collar and another underneath the lead apron at the waist. Due to partial shielding of the body by lead aprons, the Nuclear Regulatory Commission (NRC) has issued acceptable methods to calculate effective dose equivalent for these conditions. For single badge dosimetry when the film badge is placed at the collar, the reported deep dose equivalent is the effective dose equivalent [14]. If the reported deep dose equivalent is 25% of the annual limit, the effective dose will be the reported deep dose equivalent value multiplied by 0.3 [14]. For double badge dosimetry (one outside the apron at the collar and another underneath the apron at the waist), the effective dose equivalent will be the sum of the deep dose equivalent reported by the waist badge underneath the apron multiplied by 1.5 and the deep dose equivalent reported for the
collar badge outside of the apron multiplied by 0.04 [14]. The deep dose equivalent (DDE) is defined to be a measurement of equivalent dose (in rem) at a tissue depth of 10 mm and it applies to whole body exposure [14].

The use of individual monitors is primarily to ensure that the occupational worker is not receiving a radiation dose greater then 50 mSv in one year [15]. Being that there are multiple methods to determine effective dose equivalent from an individual monitor, it is important to assess how accurate they are compared to one another.

2.2 Methods and Materials

2.2.1 Issuance of Film Badges

Radiation workers in the interventional radiology and cardiac catheterization laboratory at Duke University were provided with two individual monitors and asked to place one at the collar outside of the lead apron and the other at the waist underneath the lead apron. One commercial radiation monitor vendor (Mirion Technologies, Inc., Irvine, CA) was used for the study, which took place from Fall 2010 to Fall 2011; this vendor was accredited by the National Voluntary Laboratory Accreditation Program (NVLAP).

2.2.2 Single Badge Methodology

When determining the single-badge effective dose equivalent (EDE1), the reported deep dose equivalent from the monitor placed outside the lead apron at the collar (H_{Na}) was multiplied by 0.3, as instructed in NRC 2002-06. The EDE1 was plotted against the reported collar badge reading (H_{Na}).
2.2.3 Double Badge Methodology

The double-badge effective dose equivalent (EDE2) was calculated by taking the sum of the reported deep dose equivalent from the monitor placed outside the lead apron at the collar ($H_{N}$) multiplied by 0.04 and the reported deep dose equivalent from the monitor placed underneath the lead apron at the waist ($H_{W}$) multiplied by 1.5, as instructed in NRC 2002-06. The EDE2 was plotted against the reported collar badge reading ($H_{N}$). In addition, these data points were added to a group of previously collected double-badge data from a different radiation monitor vendor (Landauer, Glenwood, IL) which was also accredited by the National Voluntary Laboratory Accreditation Program (NVLAP). The combined EDE2 data was plotted versus collar reading and was fitted by linear regression. A new equation for the $EDE2_{	ext{collar}}$ was derived for routine clinical EDE estimation.

2.3 Results and Discussion

Double badge data collected in the fall of 2010 is displayed in Table 2.1. Due to the confidential nature of this data, employee names are not listed and data points are referred to by numbers (1-7).

The raw data from points 1, 5, and 6 displayed higher waist badge readings when compared to the collar badge readings; in all of these cases the collar badge reading was reported as 0 mrem. The data points that did not wear the appropriate badge at the correct location (i.e. the waist badge was worn at the collar and vice versa) are signified by an asterisk next to the raw collar reading. This was corrected for (i.e. switch the values of the waist and collar badge readings for points 1, 5, and 6), making it apparent that none of the data points reported a waist badge reading of over 0 mrem. Due to these complications, this data was not included in the assessment of single-badge
and double-badge dosimetry. The difficulty of dose assessment in multiple badge dosimetry has been noted previously as being due to the likelihood of placing dosimeters in the wrong position or even misplacing one [16], which is confirmed by this data.

Table 2.1: Double Badge Data (Fall 2010)

<table>
<thead>
<tr>
<th></th>
<th>Monthly Period</th>
<th>Raw Waist Reading, $H_W$ (mrem)</th>
<th>Raw Collar Reading, $H_N$ (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nov-10</td>
<td>0</td>
<td>1827*</td>
</tr>
<tr>
<td>2</td>
<td>Nov-10</td>
<td>0</td>
<td>1478</td>
</tr>
<tr>
<td>3</td>
<td>Nov-10</td>
<td>0</td>
<td>2511</td>
</tr>
<tr>
<td>4</td>
<td>Nov-10</td>
<td>0</td>
<td>1393</td>
</tr>
<tr>
<td>5</td>
<td>Nov-10</td>
<td>0</td>
<td>126*</td>
</tr>
<tr>
<td>6</td>
<td>Nov-10</td>
<td>0</td>
<td>138*</td>
</tr>
<tr>
<td>7</td>
<td>Sep-10</td>
<td>0</td>
<td>137</td>
</tr>
</tbody>
</table>

Double badge data was recollected in the fall of 2011, which is displayed in Table 2.2. Due to the confidential nature of this data, employee names are not listed and data points are referred to by letters (A-E).

The plot of EDE1 versus the reported deep dose equivalent from the collar badge is displayed in Figure 2.1. A linear trend line yielded a slope of 0.3, a y-intercept of $4 \times 10^{-13}$, and an $R^2$ value of 1.

Table 2.2: Double Badge Data (Fall 2011)

<table>
<thead>
<tr>
<th></th>
<th>Monthly Period</th>
<th>Raw Waist Reading, $H_W$ (mrem)</th>
<th>Raw Collar Reading, $H_N$ (mrem)</th>
<th>EDE1 (mrem)</th>
<th>EDE2 (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Oct-11</td>
<td>53</td>
<td>729</td>
<td>218.7</td>
<td>108.66</td>
</tr>
<tr>
<td>B</td>
<td>Oct-11</td>
<td>0</td>
<td>855</td>
<td>256.5</td>
<td>34.2</td>
</tr>
<tr>
<td>C</td>
<td>Oct-11</td>
<td>67</td>
<td>1706</td>
<td>511.8</td>
<td>168.74</td>
</tr>
<tr>
<td>D</td>
<td>Oct-11</td>
<td>61</td>
<td>2515</td>
<td>754.5</td>
<td>192.1</td>
</tr>
<tr>
<td>E</td>
<td>Oct-11</td>
<td>52</td>
<td>3749</td>
<td>1124.7</td>
<td>227.96</td>
</tr>
</tbody>
</table>
The plot of EDE2 versus the reported deep dose equivalent from the collar badge is displayed in Figure 2.2. A linear trend line yielded a slope of 0.0534, a y-intercept of 44.373, and an $R^2$ value of 0.77109.

The EDE2 data was added to a collection of prior double badge data (see Appendix A) from a different manufacturer (Landauer, Glenwood, IL) and plotted against the collar badge reading; this plot is displayed in Figure 2.3. The black square signifies the EDE2 data collected prior to the fall of 2010; the red triangles signify the EDE2 data from Fall 2011. Data on EDE2 vs. collar reading were fitted by linear regression and a new equation for the EDE2_{collar} was derived for routine clinical EDE estimation; the new equation yielded a slope of 0.06992, a y-intercept of -1.682, and a $r^2$ value of 0.9081. This shows that the double badge data from the two different manufacturers follow the same pattern.
A comparison between the slopes of the single-badge equation and double-badge equations displays a difference of about a factor of 6 between the two. In all cases, there is no agreement in EDE between single- and double-badge methodologies; the single-badge method overestimated the EDE more than the double-badge method. This data demonstrates the difficulty in acquiring clinical double-badge data and also the need for an accurate equation to estimate EDE from a single badge.
Figure 2.3: Plot of Effective Dose from Double Badge (EDE2) versus Deep Dose Equivalent from Collar Badge (All Badge Data)
3. Transmission Properties of Personal Shielding Materials

3.1 Introduction

Fluoroscopy and several special procedures are the largest contributors to occupational dose in the hospital setting [3]. There are several ways to reduce occupational exposure during fluoroscopy, including minimizing beam-on time and maintaining a large distance from the radiation source [9]. In addition, protective apparel, like lead aprons and thyroid shields, is required for all personnel in the room during a fluoroscopy procedure [9]; occupational personnel use this as the primary means of radiation protection [17].

A previous study on the exposure transmission of lead aprons tested aprons from 8 different manufacturers and demonstrated that there is a significant difference in the transmission properties of lead aprons with similar lead equivalent thicknesses [17]. The transmission properties of the shielding devices used in the Duke University Medical Center should be studied since the attenuation of radiation is the method through which occupational dose is reduced.

3.2 Methods and Materials

3.2.1 Shielding Apparel

The transmission properties were studied for three lead aprons and a thyroid shield. The manufacturers and thicknesses of each of these materials are displayed in Table 3.1.
Table 3.1: Manufacturers and Thicknesses of the Protective Apparel

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Apron #1 (Lightweight)</td>
<td>Med-X Products, Inc. 0.5 mm Pb</td>
</tr>
<tr>
<td>Lead Apron #2 (Lead Free)</td>
<td>Xenolite (Dupont Technology, Lite Tech, Inc.) 0.35 mm Pb Equivalent at 100 kVp</td>
</tr>
<tr>
<td>Lead Apron #3 (Fully Leaded)</td>
<td>EZ-EM Protection 0.5 mm Pb at 85 kVp</td>
</tr>
<tr>
<td>Thyroid Shield</td>
<td>Davis Lead Apron, Inc. 0.5 mm Pb Equivalent</td>
</tr>
</tbody>
</table>

3.2.2 Exposure Parameters

The transmission properties were studied on the GE Lightspeed 64 VCT scanner (GE Healthcare, Waukesha, WI) for 80, 100, and 120 kVp. For each of these energies, the beam was set to 600 mA, 0.5 s, and 0° tube angle. In addition, the body filter and large focal spot were selected and remained constant for each exposure.

3.2.3 Ion Chamber and Electrometer

An ADCL calibrated ion chamber was used to measure the transmission properties of the shielding apparel. A 6 cc ion chamber (10x5-6, Radcal, Monrovia, CA) was used with a direct readout monitor. No chamber calibration factors were applied as the measurement of interest was a ratio of two ion chamber readings.

A Plexiglas frame was fabricated for correct placement of the protective apparel over the ion chamber. The frame measured 30.5 cm long, 30.5 cm wide, and 10 cm high with a 3.2 cm diameter hole in the middle of one side for ion chamber placement, see Figure 3.1. The positioning of a lead apron on the frame is displayed in Figure 3.2.
The table was positioned such that the active volume of the ion chamber was at the CT isocenter. The active volume is defined as the center of the ion chamber [18]. This was verified by placing a sheet of radiochromic film under the active volume and exposing the ion chamber, see Figure 3.3.

Figure 3.1: Ion Chamber in Plexiglas Frame

Figure 3.2: Placement of Lead Apron on Plexiglas Frame
Three exposure readings per energy were measured with the ion chamber in air; the average of the three was used as the in air average exposure. Three exposure readings per energy were then measured for each shielding garment; an average of the three was used as the average exposure reading for that particular shielding apparel. The standard deviation was calculated as the standard deviation from the three exposure readings. The transmission (%) was calculated by taking the ratio of the average exposure reading (for each shielding device) and the in air average exposure reading and multiplying by 100.

Figure 3.3: Verification of Correct Ion Chamber Placement in CT Beam

3.3 Results and Discussion

The measured transmission for all of the shielding garments is displayed in Figure 3.4.

It can be seen that lead apron #3 and the thyroid shield had the lowest transmission. The shielding garment with the greatest transmission was lead apron #2 (lead free). The difference between the transmission of most attenuating garments (lead apron #3 and the thyroid shield) and the other two lead aprons drastically increases
with increasing energy. The transmission values are displayed in Table 3.2. The general trend is that transmission increases for all shielding apparel with increasing energy, which can be due to the increased penetrating ability of the beam [9].

![Bar chart showing measured transmission of shielding apparel](image)

**Figure 3.4: Measured Transmission (%) of Shielding Apparel**

While occupational personnel in the radiology department receive the most exposure from scattered radiation of lower energy [3], this study did not measure attenuation tube voltages lower than 80 kVp due to the limitations of the CT scanner. However, it is expected that the percentage of transmission will only decrease at lower energies.

**Table 3.2: Measured Transmission (%) of Shielding Apparel**

<table>
<thead>
<tr>
<th>Percent Transmission (%)</th>
<th>80 kVp</th>
<th>100 kVp</th>
<th>120 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apron #1</td>
<td>3.71</td>
<td>8.07</td>
<td>12.05</td>
</tr>
<tr>
<td>Apron #2</td>
<td>7.06</td>
<td>13.04</td>
<td>17.84</td>
</tr>
<tr>
<td>Apron #3</td>
<td>3.19</td>
<td>6.58</td>
<td>7.61</td>
</tr>
<tr>
<td>Thyroid Shield</td>
<td>3.02</td>
<td>6.35</td>
<td>7.74</td>
</tr>
</tbody>
</table>
4. Accuracy of Film Badge Readings in Air

4.1 Introduction

Film badges are used as a primary method to report occupational dose in settings such as universities and hospitals that utilize x-rays [10]. Unfortunately, film badges do not allow for direct readout of exposure and must be sent to a dosimetry laboratory accredited by the NVLAP for processing and analysis [12]. While the algorithm used by the laboratory to analyze the results is not publicly known, it is important to understand the accuracy of the film badge readings. This will be accomplished by studying the film badge response compared to a calibrated ion chamber.

4.2 Materials and Methods

4.2.1 X-ray Equipment

A conventional x-ray unit in Duke Hospital North (Room H1) was used to measure the accuracy of the film badges in air. The x-ray tube information can be found in Table 4.1.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>SN #</th>
<th>Inherent Filtration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philips Medical Systems</td>
<td>9896 010 22161</td>
<td>226872</td>
<td>0.22 mm Al at 75 kVp</td>
</tr>
</tbody>
</table>

4.2.3 Piranha Detector

A Piranha detector (RTI Electronics, Fairfield, NJ) was used to measure the x-ray beam quality for tube voltages ranging from 80 to 140 kVp in 10 kVp increments in Room H1. The Piranha detector was placed on the table and was positioned such that
the positioning lasers were centered on the detector, which can be seen in Figure 4.2. The Piranha detector was irradiated three times for each energy and the readings were averaged.

![Figure 4.1: Placement of Piranha Detector in X-ray Beam](image)

### 4.2.4 Calculation of f-factor

The measured half value layer (HVL) was used to determine the effective energy of the x-ray beam at 80, 100, and 120 kVp; the effective energy was calculated from Report 78 Spectrum Processor. The f-factor, which was used to convert the exposure reading from the ion chamber to a dose measurement, was calculated using the effective energy.

\[
f = 0.869 \left( \frac{\mu_{en}}{\rho_{med}} \right) \left( \frac{\mu_{en}}{\rho_{air}} \right)
\]  \hspace{1cm} (4.1)
where $f$ is the $f$-factor, $\mu_{en}/\rho_{med}$ is the mass attenuation coefficient of the medium at each effective energy, and $\mu_{en}/\rho_{air}$ is the mass attenuation coefficient of dry air at each effective energy [19].

4.2.2 Film Badges, Ion Chamber and Electrometer

An ADCL calibrated ion chamber was used to measure the exposure while the film badges were being irradiated. A 6 cc ion chamber (10x5-6, Radcal, Monrovia, CA) was used with a direct readout monitor. The ion chamber was placed in the Plexiglas frame with two film badges positioned at either side of the active volume, see Figure 4.1. The table was positioned such that the active volume of the ion chamber was at the isocenter of the x-ray beam. The active volume is defined as the center of the ion chamber [18].

![Figure 4.2: Positioning of Ion Chamber and Film Badges in X-ray Beam](image-url)
The film badge dose per energy was taken as the average of the reported deep
dose equivalents; this is given by $D_{\text{badge}}$. The standard deviation was calculated from the
two readings.

The system coefficient of 1.022 R/Rdg was applied to the exposure
measurements of the ion chamber; the system coefficient was measured by an ADCL
and reported on 06/10/2011. The absorbed dose to soft tissue was determined from the
ion chamber exposure reading through the use of the calculated f-factor.

$$D = X \times f$$  \hspace{1cm} (4.2)

where $D$ is the absorbed dose to soft tissue in rads, $X$ is the exposure reading from the
ion chamber in Roentgens, and $f$ is the f-factor calculated for the respective energy [1].

The absorbed dose was converted to equivalent dose through the application of
the quality factor; the quality factor for photons is 1. The equivalent dose as measured
by the ion chamber is given by $D_{\text{ion}}$. The standard deviation could not be calculated for
the ion chamber measurements because only one reading was measured. The ion
chamber dose measurements were compared to the reported deep dose equivalent from
the film badges.

**4.3 Results and Discussion**

**4.3.1 HVL, Total Filtration, and f-factor Measurements**

The HVL and total filtration for different tube voltages as measured by the
Piranha detector is displayed in Table 4.2.
Table 4.2: X-Ray Beam HVL and Total Filtration Measurements

<table>
<thead>
<tr>
<th>Tube Voltage (kVp)</th>
<th>Total Filtration (mm)</th>
<th>HVL (mm Al)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>3.63</td>
<td>3.38</td>
</tr>
<tr>
<td>90</td>
<td>3.73</td>
<td>3.85</td>
</tr>
<tr>
<td>100</td>
<td>3.90</td>
<td>4.37</td>
</tr>
<tr>
<td>110</td>
<td>3.80</td>
<td>4.80</td>
</tr>
<tr>
<td>120</td>
<td>3.77</td>
<td>5.23</td>
</tr>
<tr>
<td>130</td>
<td>3.70</td>
<td>5.66</td>
</tr>
<tr>
<td>140</td>
<td>3.60</td>
<td>6.08</td>
</tr>
</tbody>
</table>

The effective energy, mass attenuation coefficients of soft tissue and air, and calculated f-factor are displayed in Table 4.3. The mass attenuation coefficients of soft tissue and air were given by the National Institute of Standards and Technology (NIST).

Table 4.3: Effective Energy and f-factor for Various Tube Voltages

<table>
<thead>
<tr>
<th>Tube Voltage (kVp)</th>
<th>Effective Energy (keV)</th>
<th>(\mu_{en}/\rho) (soft tissue)</th>
<th>(\mu_{en}/\rho) (Air)</th>
<th>f-factor (rad/R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>45.0</td>
<td>0.05788</td>
<td>0.05466</td>
<td>0.9202</td>
</tr>
<tr>
<td>100</td>
<td>51.6</td>
<td>0.04185</td>
<td>0.03929</td>
<td>0.9256</td>
</tr>
<tr>
<td>120</td>
<td>56.9</td>
<td>0.03604</td>
<td>0.03369</td>
<td>0.9296</td>
</tr>
</tbody>
</table>

4.3.2 Film Badge and Ion Chamber Measurements

The equivalent dose as measured by the ion chamber, reported deep dose equivalent from the film badge, and percent difference between the two is displayed in Table 4.4. The standard deviations of the film badge readings, given in percentages, are found in the respective column.
Table 4.4: Reported Film Badge Dose, Ion Chamber Equivalent Dose, and Percent Difference

<table>
<thead>
<tr>
<th>Exposure Parameters</th>
<th>$D_{\text{badge}}$ (mSv)</th>
<th>$D_{\text{ion}}$ (mSv)</th>
<th>Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 kVp 200.0 mA 80.0 ms</td>
<td>3.50 (±1.01%)</td>
<td>4.63</td>
<td>24.5</td>
</tr>
<tr>
<td>100 kVp 160.0 mA 80.0 ms</td>
<td>4.80 (±7.37%)</td>
<td>5.83</td>
<td>17.7</td>
</tr>
<tr>
<td>120 kVp 125.0 mA 80.0 ms</td>
<td>4.90 (±14.14%)</td>
<td>6.49</td>
<td>24.5</td>
</tr>
</tbody>
</table>

A plot of the film badge dose and ion chamber dose is displayed in Figure 4.3. Compared to the equivalent dose calculated from the ion chamber measurements, the film badge reading underestimated the dose by 24.5%, 17.7%, and 24.5% for 80, 100, and 120 kVp, respectively. The film badge dose was taken as the reported deep dose equivalent (DDE) which is the dose for strongly penetrating radiation at a depth of 10 mm [14]; this may be the reason for the discrepancy between the ion chamber and film badge readings.

![Figure 4.3: Comparison of Film Badge Dose and Ion Chamber Dose](image)

Figure 4.3: Comparison of Film Badge Dose and Ion Chamber Dose
5. Effective Dose Estimation Using Single and Double Badges

5.1 Introduction

Film badges have been used in the radiology department for decades as a means of monitoring occupational dose [9]. NRC regulations state that annual occupational exposure must not exceed 50 mSv [5]. Being that occupational exposure is extremely non-uniform due to shielding of the trunk by the lead apron, using the single badge methodology (where one monitor is placed at the collar outside of the lead apron) may be an extremely conservative estimate [16]. A more accurate approach would be the double badge methodology, where one badge is outside the lead apron at the collar and another badge is underneath the lead apron at the waist [16]. There have been several methodologies, including Gill’s, Webster’s, and Niklason’s methodologies, that have been proposed to convert from film badge reading to effective dose.

J.R. Gill et. al. derived an equation pertaining to the organs unprotected and protected by the lead apron and their respective weighting factors. This methodology used the weighting factors specified by ICRP 26 (1977). The proposed equation had a conversion coefficient (CC) of 0.6 for the waist badge and 0.4 for the collar badge [20]. The double badge methodology that is most commonly used and which is recommended by NRC 2002-06, is Webster’s methodology; this also uses weighting factors from ICRP 26 (1977). This equation yielded a CC of 1.5 for the waist badge and 0.04 for the collar badge [21]. Lastly, L.T. Niklason et. al. derived another methodology by using the under-apron dose as the whole body dose. Organ dose tables for an anterioposterior (AP) projection of the skull and cervical spine and collar dose
measurements were used to estimate effective dose in the head and neck. Niklason’s methodology yielded two equations:

\[ E = 0.06(H_{os} - H_u) + H_u \]  \hspace{1cm} (5.1)

\[ E = 0.02(H_{os} - H_u) + H_u \]  \hspace{1cm} (5.2)

where \( H_{os} \) is the reported shallow dose at the collar and \( H_u \) is the deep dose equivalent for the waist badge [11]. The first equation pertains to an occupational worker without a thyroid shield and the second equation pertains to an occupational worker with a thyroid shield [11].

It is evident that there have been various ways proposed to estimate effective dose from double badge dosimetry. However, many of these methodologies, including the equation recommended by NRC 2002-06, use outdated weighting factors from ICRP 26. In addition, there are many difficulties found in accurately collecting double badge data as noted in Chapter 2; the simpler way to collect badge data is by using the single badge method. However, there may also be inaccuracies in estimating effective dose for single badge dosimetry. For example, NRC 2002-06 recommends using the deep dose equivalent as the effective dose for single badge dosimetry unless the DDE exceeds 25% of the annual limit [14]. Therefore, it is important to determine more accurate conversion coefficients for the single badge methodology.

5.2 Methods and Materials

5.2.1 Phantom

An adult male anthropomorphic phantom (701-D Adult Male Complete Phantom, CIRS, Norfolk, VA) was used for all organ dose measurements. The phantom
simulates different tissue types, including bone, soft tissue, spinal cord, spinal disks, lung, and brain [22]. The phantom material specifications can be found in Table 5.1.

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Physical Density (g/cc)</th>
<th>Electron Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult Bone</td>
<td>1.60</td>
<td>5.030 x 10^{23}</td>
</tr>
<tr>
<td>Soft Tissue</td>
<td>1.05</td>
<td>3.434 x 10^{23}</td>
</tr>
<tr>
<td>Spinal Cord</td>
<td>1.07</td>
<td>3.448 x 10^{23}</td>
</tr>
<tr>
<td>Spinal Disks</td>
<td>1.15</td>
<td>3.694 x 10^{23}</td>
</tr>
<tr>
<td>Lung</td>
<td>0.21</td>
<td>0.681 x 10^{23}</td>
</tr>
<tr>
<td>Brain</td>
<td>1.07</td>
<td>3.470 x 10^{23}</td>
</tr>
</tbody>
</table>

The phantom was loaded with 20 diagnostic MOSFET detectors, which is displayed in Figure 5.1. The MOSFET detectors were individually calibrated in air using a conventional x-ray tube with added filtration prior to this study. The beam quality of the conventional x-ray tube was matched to the beam quality of the CT scanner used for the organ dose measurements. Organ locations for each of the MOSFET detectors are displayed in Table 5.2. Two film badges were placed on the phantom in accordance with double badge placement: one at the collar and one at the waist, displayed in Figure 5.1.
Table 5.2: MOSFET Locations in Phantom

<table>
<thead>
<tr>
<th>MOSFET</th>
<th>Location</th>
<th>MOSFET</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Brain</td>
<td>C1</td>
<td>Pancreas</td>
</tr>
<tr>
<td>A2</td>
<td>Lens of Left Eye</td>
<td>C2</td>
<td>Left Kidney</td>
</tr>
<tr>
<td>A3</td>
<td>Thyroid</td>
<td>C3</td>
<td>Liver</td>
</tr>
<tr>
<td>A4</td>
<td>Lungs (Middle)</td>
<td>C4</td>
<td>Bone Marrow - T-Spine</td>
</tr>
<tr>
<td>A5</td>
<td>Thymus</td>
<td>C5</td>
<td>Intestine</td>
</tr>
<tr>
<td>B1</td>
<td>Skin</td>
<td>D1</td>
<td>Bone Marrow - L-Spine</td>
</tr>
<tr>
<td>B2</td>
<td>Esophagus/Heart Wall</td>
<td>D2</td>
<td>Bone Marrow - Pelvis</td>
</tr>
<tr>
<td>B3</td>
<td>Bone Marrow - Ribs</td>
<td>D3</td>
<td>Uterus/Bladder</td>
</tr>
<tr>
<td>B4</td>
<td>Spleen</td>
<td>D4</td>
<td>Testes</td>
</tr>
<tr>
<td>B5</td>
<td>Stomach</td>
<td>D5</td>
<td>Left Breast</td>
</tr>
</tbody>
</table>

5.2.2 Scan Parameters

Organ doses were measured using a GE VCT 64 slice scanner. The whole body protocol was used at three different energies. Scan parameters for each energy are displayed in Table 5.3. For each scan, the tube current was set manually and automatic tube current modulation was not employed.
Table 5.3: GE VCT Scan Parameters

<table>
<thead>
<tr>
<th>Protocol</th>
<th>kVp</th>
<th>mAs</th>
<th>CTDI_{vol} (mGy)</th>
<th>DLP (mGy-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole Body</td>
<td>80</td>
<td>600</td>
<td>5.59</td>
<td>547.23</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>650</td>
<td>12.1</td>
<td>1185.66</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>500</td>
<td>15.02</td>
<td>1471.04</td>
</tr>
</tbody>
</table>

5.2.3 Effective Dose Measurements

The phantom, loaded with MOSFETS, was subjected to the scans listed above. The organ doses were measured and recorded after each run; there were three runs for each energy. In some cases, as many as three scans were performed for each run because doses were too low to accurately read from a single scan. The organ doses were measured a total of three times and the effective dose was calculated using the average dose to each organ. The standard deviation was calculated for each organ dose and effective dose. The effective dose for each scan was computed using the ICRP 103 tissue weighting factors. The measured organ dose was multiplied by the corresponding organ weighting factor, which is displayed in Table 5.4. The remainder consists of adrenals, extrathoracic tissues, gall bladder, heart wall, kidneys, lymph nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, and uterus/cervix [23].

The effective dose was calculated for both the male and female phantom by using the testes as the male gonads and ovaries as the female gonads. The average of the male and female effective dose was used as the final effective dose.

\[
ED = \sum w_T H_T
\]

(5.3)

where \( ED \) is the effective dose, \( w_T \) is the tissue weighting factor, and \( H_T \) is the equivalent dose for organ \( T \) [23].
In order to correct for the lead apron attenuation, the effective dose was multiplied by the lead apron transmission for the respective energy (found in Table 3.2); the effective dose corrected for attenuation is given by $ED_{Atten}$.

### 5.2.4 Film Badge Measurements

Two film badges were placed on the phantom during the scans: one at the collar and one at the waist. The same film badges remained on the phantom during the three runs; the reported reading was divided by the product of the number of scans per run and the number of runs per protocol. The film badges were then changed out prior to starting a new set of runs with a different energy.

In order to correct for lead apron attenuation, the waist badge reading was multiplied by the lead apron transmission (see Table 3.2); the attenuation corrected waist badge reading is given by $H_{W,Atten}$. Both EDE1 and EDE2 were calculated from the reported deep dose equivalent of the collar ($H_N$) and waist ($H_{W,Atten}$) badge in accordance with NRC 2002-06 recommendations (sections 2.2.2 and 2.2.3).
Table 5.4: ICRP 103 Organ Weighting Factors

<table>
<thead>
<tr>
<th>Organ</th>
<th>Weighting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0.08</td>
</tr>
<tr>
<td>Bone Marrow (Red)</td>
<td>0.08</td>
</tr>
<tr>
<td>Colon</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.04</td>
</tr>
<tr>
<td>Breast</td>
<td>0.12</td>
</tr>
<tr>
<td>Liver</td>
<td>0.04</td>
</tr>
<tr>
<td>Esophagus</td>
<td>0.04</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.04</td>
</tr>
<tr>
<td>Skin</td>
<td>0.01</td>
</tr>
<tr>
<td>Bone Surface</td>
<td>0.01</td>
</tr>
<tr>
<td>Salivary Glands</td>
<td>0.01</td>
</tr>
<tr>
<td>Brain</td>
<td>0.01</td>
</tr>
<tr>
<td>Remainder</td>
<td>0.12</td>
</tr>
</tbody>
</table>

5.2.5 Single Badge Effective Dose Conversion Coefficient Estimation

The conversion coefficient (CC) to convert from collar badge reading to effective dose was calculated for each energy.

\[
CC = \frac{ED_{\text{Aoral}}}{H_N} \tag{5.4}
\]
where \( CC \) is conversion coefficient, \( ED_{Atten} \) is attenuation corrected effective dose calculated from MOSFET organ dose data, and \( H_N \) is the reported deep dose equivalent from the collar badge.

Since only one collar badge was used for all three runs at one energy, the single badge standard deviation could not be calculated from the badge readings alone. Instead, it was assumed that the ratio of the standard deviation and average badge reading from the in-air experiment (see Chapter 4) would be the same for the collar badge readings from this experiment.

\[
\Delta H_N = (H_N) \left( \frac{\Delta H_{N-In-Air}}{H_{N-In-Air}} \right)
\]  

(5.5)

where \( \Delta H_N \) is the standard deviation of the reported deep dose equivalent from the collar badge, \( H_N \) is the reported deep dose equivalent from the collar badge, \( \Delta H_{N-In \, Air} \) is the standard deviation of the reported deep dose equivalent from the in-air collar badge reading, and \( H_{N-In \, Air} \) is the reported deep dose equivalent from the in-air collar badge reading.

The standard deviation of the single badge conversion coefficient was calculated for each energy using the propagation of error.

\[
\Delta CC = \left( \frac{ED_{Atten}}{H_N} \right) \left[ \left( \frac{\Delta ED_{Atten}}{ED_{Atten}} \right)^2 + \left( \frac{\Delta H_N}{H_N} \right)^2 \right]^{1/2}
\]  

(5.6)

where \( \Delta CC \) is the conversion coefficient standard deviation, \( ED_{Atten} \) is the attenuation corrected effective dose from MOSFET organ dose data, \( \Delta ED_{Atten} \) is the standard deviation of attenuation corrected effective dose, \( H_N \) is the reported deep dose equivalent from the collar badge, and \( \Delta H_N \) is the standard deviation of the reported deep dose equivalent from the collar badge.
5.3 Results and Discussion

5.3.1 Effective Dose

The measured effective dose for each protocol is displayed in Figure 5.2. It can be seen from the figure that the effective dose increases with increasing energy.

![Figure 5.2: Measured Effective Dose](image)

The measured effective dose and attenuation corrected effective dose can be found in Table 5.5.

**Table 5.5: Measured Effective Dose and Attenuation Corrected Effective Dose**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>ED (mSv)</th>
<th>ΔED (mSv)</th>
<th>ED_{Atten} (mSv)</th>
<th>ΔED_{Atten} (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 kVp</td>
<td>7.14</td>
<td>1.06</td>
<td>0.50</td>
<td>0.07</td>
</tr>
<tr>
<td>100 kVp</td>
<td>16.42</td>
<td>0.98</td>
<td>2.14</td>
<td>0.13</td>
</tr>
<tr>
<td>120 kVp</td>
<td>27.90</td>
<td>1.92</td>
<td>4.98</td>
<td>0.34</td>
</tr>
</tbody>
</table>

5.3.2 Film Badge Measurements

The reported deep dose equivalent from the collar badge, attenuation corrected deep dose equivalent from the waist badge, EDE1, and EDE2 are displayed in Table 5.6.
Table 5.6: Reported Collar and Waist Badge Readings and Corresponding EDE1 and EDE2

<table>
<thead>
<tr>
<th>Protocol</th>
<th>H_N (mSv)</th>
<th>H_W-Atten (mSv)</th>
<th>EDE1 (mSv)</th>
<th>EDE2 (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 kVp</td>
<td>38.84</td>
<td>1.68</td>
<td>11.65</td>
<td>4.07</td>
</tr>
<tr>
<td>100 kVp</td>
<td>92.82</td>
<td>8.82</td>
<td>27.85</td>
<td>16.94</td>
</tr>
<tr>
<td>120 kVp</td>
<td>128.64</td>
<td>13.52</td>
<td>38.59</td>
<td>25.43</td>
</tr>
</tbody>
</table>

The measured effective dose (MOSFET ED), EDE1, and EDE2 is displayed in Figure 5.3. Compared to the MOSFET ED, EDE1 and EDE2 overestimates ED by factors of about 7 and 5, respectively.

Figure 5.3: Measured Effective Dose, EDE1 and EDE2

5.3.3 Single Badge Effective Dose Conversion Coefficient Estimation

The conversion coefficient and standard deviation for each energy is displayed in Table 5.7. The standard deviation was 14.88%, 9.49%, and 15.74% of the conversion coefficient at 80, 100, and 120 kVp, respectively.
Table 5.7: Calculated Conversion Coefficient and Standard Deviation

<table>
<thead>
<tr>
<th>Protocol</th>
<th>CC</th>
<th>ΔCC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 kVp</td>
<td>0.01</td>
<td>0.002 (14.88)</td>
</tr>
<tr>
<td>100 kVp</td>
<td>0.02</td>
<td>0.002 (9.49)</td>
</tr>
<tr>
<td>120 kVp</td>
<td>0.04</td>
<td>0.006 (15.74)</td>
</tr>
</tbody>
</table>

The reported deep dose equivalent was plotted against the measured effective dose from the MOSFET organ doses in Figure 5.4. Linear regression analysis was used to determine a new equation to determine effective dose from collar badge reading; this equation yielded a slope of 0.0483 and a y-intercept of -1.6517. The fit of the data displayed in Figure 5.4 is not perfectly linear which is given by the R² value of 0.92929. This is perhaps due to the fact that the relationship between ED and kVp is exponential in nature and varies approximately to the power of 2 (i.e. ED increases by kVp²) [24].

![Figure 5.4: Collar Badge Reading Versus Measured Effective Dose](image-url)

The current regulatory ED conversion coefficient with the single collar
badge is 0.3; the CCs for the double-badge system are 0.04 (collar) and 1.5 (waist). Based on the findings, the single badge CC of 0.3 should be dropped as it overestimates ED. Being that occupational workers receive most of their exposure from scattered radiation of lower energy [3], a CC of 0.01 (80 kVp data) may be a viable option rather than the current regulatory CC of 0.3. The double badge system seems to provide a better collar CC as 0.04 (as seen in Figure 5.4); however, exposure readings under the apron are usually negligible to zero with lead aprons (see Section 2.3). While the calculated CC from this experiment provide a crude estimate of ED using the single badge method, more work should be done evaluating the accuracy of the CC.
6. Organ Dose and Image Quality in MDCT Thoracic Scans: A Comparison of Bismuth Shielding and a Universal Reduction in Tube Current

6.1 Introduction

The evolution of three-dimensional medical imaging has lead to an increase in the number of CT scans per year [25]. As the number of CT scans increases, dose reduction techniques must be considered in order to keep patient dose at a minimum. These techniques include reducing tube current time product (mAs), increasing the pitch, and reducing tube voltage (kVp), all of which have the resulting consequence of reducing image quality [25]. As an alternative approach, bismuth shields, which attenuate lower energy photons, may also be used in CT scans. It is known that lower energy photons contribute significantly to dose but not to image formation [26]; thus, shielding radiosensitive organs of the body (i.e. breasts, thyroid, and lens of the eye) have demonstrated a resulting decrease in dose to those areas [27-29]. The use of bismuth shields has also been associated with a decrease in image quality, which includes an increase in beam hardening artifacts, image noise, and a consequent shift in HU values [27-29].

Both the image quality and reduction of dose to the breast have been studied with the use of bismuth shields in thoracic CT scans. Yilmaz et al determined that the glandular breast dose was reduced by 40.52% when measured with human patients and 17.33% when measured with an anthropomorphic phantom [27]. In all cases, the left breast was shielded while the right breast was unshielded and the dose was measured with TLD dosimeters [27]. It was noted that artifacts were present in the superficial breast tissue but not in the parenchyma or mediastinum [27]. Another study determined
through Monte Carlo simulations that the bismuth shield reduced the dose by 30% to the breast and 15% to the lungs [28]. This study also considered image quality by subjecting an anthropomorphic phantom to a chest CT scan, in which it was seen that beam-hardening artifacts along with an increase in noise were present at the level of the shield [28]. A limitation in this study was that the shield was placed with no gap between the anterior surface of the phantom and the shield, which is a probable cause for the artifacts in the resultant image. In addition, both of these studies only considered using a bismuth shield as the dose reduction technique and did not perform experiments with any of the other dose reduction techniques noted above.

More recently, a study was conducted comparing the technique of global tube current reduction to bismuth shielding. The lowered tube current value was reduced to match the same dose reduction as achieved by the bismuth shield at the anterior surface [29]. The dose measured at the anterior surface of the thorax was reduced by about 20-40% for both the lower mA and bismuth shield technique [29]. The noise increase also remained about the same for both the lower mA and bismuth shield technique and was determined to increase about 2-4 HU [29]. When comparing HU values, there was an increase of about 10-20 HU in the scan with the bismuth shield while there was no increase in the lower tube current scan [29]. A limitation in this study dealt with the position of the bismuth shield on the semi-anthropomorphic phantom, which did not have a “smooth” placement over the breast tissue. The placement in which the shield appears to have a smooth rounded surface has been seen to decrease streak artifacts [30]. In addition, important image quality measures, such as signal-to-noise ratio (SNR) and percent contrast (%Contrast), were not evaluated during this study. It is important for such measures to be quantified so that all areas of image quality can be assessed.
6.2 Materials and Methods

6.2.1 Phantom

An adult male anthropomorphic phantom (701-D Adult Male Complete Phantom, CIRS, Norfolk, VA) was used for all organ dose measurements. The phantom simulates different tissue types, including bone, soft tissue, spinal cord, spinal disks, lung, and brain [22]. The phantom material specifications can be found in Table 5.1.

The phantom was loaded with 20 diagnostic MOSFET detectors, which is displayed in Figure 6.1. The MOSFET detectors were individually calibrated in air using a conventional x-ray tube with added filtration prior to this study. The beam quality of the conventional x-ray tube was matched to the beam quality of the CT scanner used for the organ dose measurements. Organ locations for each of the MOSFET detectors are displayed in Table 6.1.

Figure 6.1: Anthropomorphic Phantom with Ion Chamber and MOSFETS
Table 6.1: MOSFET Locations in Phantom

<table>
<thead>
<tr>
<th>MOSFET</th>
<th>Location</th>
<th>MOSFET</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Liver</td>
<td>C1</td>
<td>Bone Marrow - Ribs</td>
</tr>
<tr>
<td>A2</td>
<td>Lung (Lower)</td>
<td>C2</td>
<td>Thymus</td>
</tr>
<tr>
<td>A3</td>
<td>Esophagus (Lower)</td>
<td>C3</td>
<td>Bone Marrow - Sternum</td>
</tr>
<tr>
<td>A4</td>
<td>Lung (Middle)</td>
<td>C4</td>
<td>Lung (Upper)</td>
</tr>
<tr>
<td>A5</td>
<td>Right Breast</td>
<td>C5</td>
<td>Esophagus (Upper)</td>
</tr>
<tr>
<td>B1</td>
<td>Left Breast</td>
<td>D1</td>
<td>Thyroid (Lower Right)</td>
</tr>
<tr>
<td>B2</td>
<td>Axillary Lymph Nodes</td>
<td>D2</td>
<td>Thyroid (Upper Left)</td>
</tr>
<tr>
<td>B3</td>
<td>Heart</td>
<td>D3</td>
<td>Bone Marrow - Mandible</td>
</tr>
<tr>
<td>B4</td>
<td>Lung (Middle)</td>
<td>D4</td>
<td>Left Breast (3 o’clock)</td>
</tr>
<tr>
<td>B5</td>
<td>Bone Marrow - T-Spine</td>
<td>D5</td>
<td>Skin</td>
</tr>
</tbody>
</table>

6.2.2 Scan Parameters

Organ doses were measured using a GE VCT 64 slice scanner using the Pulmonary Embolus (PE) protocol. The phantom was scanned at 120 kVp with a pitch of 1.375:1 for each protocol. Scan parameters are displayed in Table 6.2. The TCM protocol was used as the reference scan and utilized tube current modulation (TCM) without the Bismuth shield being present. The TCM With Bismuth protocol utilized the same scan parameters as the reference scan but with the addition of the in-plane Bismuth shield (4-ply); the placement of the Bismuth shield on the phantom is displayed in Figure 6.2. The reduced tube current (RTC) protocol did not employ TCM and required the tube current to be set manually.

6.2.3 Ion Chamber and Electrometer

An ADCL calibrated ion chamber was used to measure the reference exposure for the TCM (Reference) protocol and the exposure underneath the Bismuth shield for the TCM With Bismuth Protocol. An 0.18 cc ion chamber (10x5-0.18, Radcal, Monrovia, CA) was placed on the phantom at the level of the breast, which is displayed in Figure
6.1. This ion chamber was used with a direct readout monitor. No chamber calibration factors were applied as the measurement of interest was required a ratio of two ion chamber readings.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>kVp</th>
<th>mA</th>
<th>Exposure Time (s)</th>
<th>CTDI$_{vol}$ (mGy)</th>
<th>DLP (mGy-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCM (Reference)</td>
<td>120</td>
<td>697</td>
<td>6.2</td>
<td>37.41</td>
<td>1414.57</td>
</tr>
<tr>
<td>TCM With Bismuth</td>
<td>120</td>
<td>697</td>
<td>6.2</td>
<td>37.41</td>
<td>1414.57</td>
</tr>
<tr>
<td>RTC</td>
<td>120</td>
<td>415</td>
<td>6.2</td>
<td>22.43</td>
<td>848.33</td>
</tr>
</tbody>
</table>

Figure 6.2: Placement of Bismuth Shield on Phantom

The tube current for the RTC scan was determined from the ion chamber exposure readings.

$$mA_{\text{low}} = mA_{\text{ref}} \left( \frac{X_{\text{shield}}}{X_{\text{ref}}} \right)$$  \hspace{1cm} (6.1)
where $mA_{\text{low}}$ is the tube current for the RTC protocol, $mA_{\text{ref}}$ is the tube current for the Reference protocol, $X_{\text{shield}}$ is the ion chamber exposure reading for the TCM With Bismuth protocol, and $X_{\text{ref}}$ is the ion chamber exposure reading for the Reference protocol.

### 6.2.4 Image Quality Calculations

Regions of interest (ROIs) were drawn in the lung, heart, and breast. The ROIs were drawn in slice 149 on four different data sets. Since the HU scale of a CT scanner contains both positive and negative values (the minimum value is -1000 corresponding to air and maximum lies at +1000 corresponding to bone), the raw average Hounsfield Unit (HU) of each ROI was rescaled so that it fell between 0 and 2000; this was done by adding the value of 1000 to all raw HU values. Once the raw value was rescaled, it was used as the signal for each ROI. The standard deviation (SD) of HU was used as the noise for each ROI. The reconstructed slice thickness was 1.25 mm. The placement of the ROIs is displayed in Figure 6.3. The nominal area of the ROIs was 1.106 cm$^2$.

The average HU and SD for each of the 6 lung ROIs were averaged and used as the lung signal and noise, respectively. The average HU and SD for each of the 2 heart ROIs were averaged and used as the heart signal and noise, respectively. The average HU and SD for each of the 2 breast ROIs were averaged and used as the breast signal and noise, respectively.
A lung insert with high contrast cylindrical targets (CIRS, Norfolk, VA) was inserted into the phantom in slices 13 and 14. The lung insert contains three cylindrical targets for each diameter; the diameters are 7, 5, 3.5, 2.5, 1.8, and 1.2 mm [31]. The lung insert is displayed in Figure 6.4.

Regions of interest (ROIs) were drawn in the three 7 mm cylindrical targets, in the region of lung surrounding the lung insert, and in several areas of the lung not surrounding the lung insert. The ROIs were drawn in 10 adjacent slices (slice 96-105); the average Hounsfield Unit (HU) was used as the signal for each ROI and the average standard deviation of HU was used as the noise for each ROI. The reconstructed slice thickness was 1.25 mm. The placement of the ROIs and lung insert are displayed in Figure 6.5. The nominal area of the ROIs was 0.119 cm².
The Hounsfield Unit (HU) of the most lateral ROIs in the 7 mm cylindrical targets was used as the object signal for each of the 10 slices; this ROI had the most consistent HU among the 10 slices. The standard deviation of the object signal was taken as the SD of the most lateral ROI in the 7 mm cylindrical targets. The average HU of the seven lung ROIs was used as the background signal for each of the 10 slices. The standard deviation of the background signal was calculated as the standard deviation of the HUs from the 7 lung ROIs per slice. The average noise of the seven lung ROIs was used as the background noise for each of the 10 slices.
The signal-to-noise ratio (SNR) was calculated for each protocol.

$$\text{SNR} = \frac{(H_{\text{object}} - H_{\text{background}})}{\sigma_{\text{background}}}$$  (6.2)

where $H_{\text{object}}$ is the object signal, $H_{\text{background}}$ is the background signal, and $\sigma_{\text{background}}$ is the noise of the background signal [24].

The standard deviation was calculated for each SNR through the propagation of error.

$$\Delta \text{SNR} = \text{SNR} \left[ \frac{\sqrt{\Delta H_{\text{object}}^2 + \Delta H_{\text{background}}^2}}{H_{\text{object}} - H_{\text{background}}} \right]^{2}$$  (6.3)

where $\Delta \text{SNR}$ is the standard deviation of the SNR, SNR is the signal-to-noise ratio, $H_{\text{object}}$ is the object signal, $\Delta H_{\text{object}}$ is the standard deviation of the object signal, $H_{\text{background}}$ is the background signal, and $\Delta H_{\text{background}}$ is the standard deviation of the background signal.

The percent contrast (% Contrast) was also calculated for each protocol.
\[
\%\text{Contrast} = \left( \frac{\text{HU}_{\text{object}} - \text{HU}_{\text{background}}}{\text{HU}_{\text{background}} - \text{HU}_{\text{air}}} \right) \times 100
\]  
(6.4)

where \( \text{HU}_{\text{object}} \) is the object signal, \( \text{HU}_{\text{background}} \) is the signal of the lung, and \( \text{HU}_{\text{air}} \) is the signal of air (\( \text{HU}_{\text{air}} = -1000 \)) [24].

The standard deviation was calculated for each \( \%\text{Contrast} \) through the propagation of error.

\[
\Delta \%\text{Contrast} = \%\text{Contrast} \left( \frac{\sqrt{\Delta \text{HU}_{\text{object}}^2 + \Delta \text{HU}_{\text{background}}^2}}{\text{HU}_{\text{object}} - \text{HU}_{\text{background}}} \right)^2 + \left( \frac{\Delta \text{HU}_{\text{background}}}{\text{HU}_{\text{background}}} \right)^2
\]  
(6.5)

where \( \Delta \%\text{Contrast} \) is the standard deviation of the \( \%\text{Contrast} \), \( \%\text{Contrast} \) is the percent contrast, \( \text{HU}_{\text{object}} \) is the object signal, \( \Delta \text{HU}_{\text{object}} \) is the standard deviation of the object signal, \( \text{HU}_{\text{background}} \) is the background signal, and \( \Delta \text{HU}_{\text{background}} \) is the standard deviation of the background signal.

### 6.2.5 Piranha Detector

A Piranha detector (RTI Electronics, Fairfield, NJ) was used to measure the x-ray beam quality for 120 kVp in-air and underneath the Bismuth shield. The Piranha detector was placed on the table and was positioned such that the positioning lasers were centered on the detector, which can be seen in Figure 6.6. The tube was set to an angle of 0°.

After the half value layer (HVL) and total filtration were measured in air, the Bismuth shield was placed over the Piranha detector to measure the beam quality after exiting the shield.
6.3 Results and Discussion

6.3.1 Ion Chamber Exposure Readings

The measured exposure from the ion chamber for the TCM, TCM With Bismuth, and RTC protocols is displayed in Table 6.3.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Ion Chamber Exposure (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCM</td>
<td>8.40 (±1.2%)</td>
</tr>
<tr>
<td>TCM With Bismuth</td>
<td>4.99 (±0.25%)</td>
</tr>
<tr>
<td>RTC</td>
<td>4.29 (±18.5%)</td>
</tr>
</tbody>
</table>

Compared to the TCM scan, the TCM With Bismuth and RTC display an exposure reduction of about 35% and 44%, respectively. Bismuth shields remove lower-energy photons, which contribute to patient dose but not to image formation [26], thus reducing the total number of photons. Since the tube current is proportional to the number of photons produced [9], lowering the tube current results in a lower amount of
 photons reaching the ion chamber. Therefore, both the TCM With Bismuth and RTC protocols result in a lower amount of photons reaching the ion chamber which explains the decreased exposure.

### 6.3.2 Organ Dose

The absorbed dose to the thoracic organs for the TCM, TCM With Bismuth, and RTC protocols are displayed in Figure 6.7.

Compared to the TCM protocol, the TCM With Bismuth and RTC protocols provide a dose reduction to the breast of about 40%. The dose reduction varies from 2% to 25% for the organs in the TCM With Bismuth protocol; the inconsistency of dose reduction across the entire scan is due to the fact that the Bismuth shield is only located at the level of the breast. For the RTC protocol, the dose reduction to organs other than the breast does not vary as much as the TCM With Bismuth protocol and ranges from 40% to 50%. The RTC protocol produces a global reduction in dose because reducing the tube current reduces the number of photons produced [9], which reduces patient dose that can be seen throughout the entire scan.

![Figure 6.7: Organ Dose for TCM, TCM With Bismuth, and RTC Protocols](image)
6.3.3 Hounsfield Unit (HU) Uniformity and Noise

The average signal in HUs in the lung for the TCM, TCM With Bismuth, and RTC protocols are displayed in Figure 6.8. The average HU in the lung for the TCM scan was -785.9. The average HU in the lung was -774.9 for the TCM With Bismuth scan; this represents an increase of about 11 HU compared to the TCM scan. The average HU in the lung was -785.9 for the RTC scans, which represents no increase or decrease in HUs compared to the TCM scan.

![Figure 6.8: Average Lung Signal](image)

The average signal in HUs in the breast for the TCM, TCM With Bismuth, and RTC protocols are displayed in Figure 6.9. The average HU in the breast for the TCM scan was -44.3. The average HU in the breast was 3.17 for the TCM With Bismuth scan; this represents an increase of about 46 HU compared to the TCM scan. The average HU in the breast was -44.6 for the RTC scans, which represents a 0.3 decrease in HUs compared to the TCM scan.
Figure 6.9: Average Breast Signal

The average signal in HUs in the heart for the TCM, TCM With Bismuth, and RTC protocols are displayed in Figure 6.10. The average HU in the heart for the TCM scan was 19.5. The average HU in the heart was 28.5 for the TCM With Bismuth scan; this represents an increase of about 9 HU compared to the TCM scan. The average HU in the heart was 19.2 for the RTC scans, which represents a 0.3 decrease in HUs compared to the TCM scan.
The average noise in HUs in the lung, breast, and heart for the TCM, TCM With Bismuth, and RTC protocols are displayed in Figure 6.11.

Figure 6.11: Average Noise in the Lung, Breast, and Heart
The mean noise in the TCM With Bismuth and RTC protocols increased by 5.5% and 14.2% in the lung, 44.6% and 28.4% in the breast, and 29.1% and 27.7% in the heart, respectively. While the Bismuth shield was placed only on the anterior surface of the phantom, the increased noise was expected due to the attenuation of x-ray photons in the anterior and posterior direction by the shield before reaching the detector. It is known that decreasing the amount of photons reaching the detectors increases the image noise [26]. Increased noise was expected for the RTC protocol because decreasing the tube current also results in a decreased number of photons [26].

### 6.3.4 Signal-to-Noise Ratio (SNR) and Percent Contrast (% Contrast)

The SNR and % Contrast normalized to the TCM scan for the TCM, TCM With Bismuth, and RTC protocols are displayed in Figures 6.12 and 6.13.

![Figure 6.12: SNR for TCM, TCM With Bismuth, and RTC Protocols](image)

Compared to the TCM protocol, the SNR decrease in the TCM With Bismuth and RTC protocols were 17.3% and 23.1%, respectively. A paired t-test was used to determine that the difference in mean SNR was statistically significant for both the TCM
With Bismuth (p = 0.0003) and RTC (p < 0.0001) protocols. The decreased SNR was expected due to the increase in noise for both the TCM With Bismuth and RTC scans [1].

The % Contrast for the TCM With Bismuth and RTC scans decreased by 6.1% and 1.8%, respectively. A paired t-test was used to determine that the difference in mean %Contrast was statistically significant with p < 0.001 for both the TCM With Bismuth and RTC protocols. Beam energy is known to have an inverse relationship with contrast [26]; the decreased contrast in the TCM With Bismuth scan may be due to an increase in the effective energy of the beam after passing through the Bismuth shield.

![Figure 6.13: %Contrast for TCM, TCM With Bismuth, and RTC Protocols](image)

### 6.3.5 CT Beam Spectra

The half value layer (HVL) and total filtration of the beam in-air and after passing through the Bismuth shield is displayed in Table 6.4.

<table>
<thead>
<tr>
<th></th>
<th>HVL (mm)</th>
<th>Total Filtration (mm Al)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Air</td>
<td>9.0</td>
<td>7.59</td>
</tr>
<tr>
<td>With Bismuth</td>
<td>18.0</td>
<td>9.26</td>
</tr>
</tbody>
</table>

![Table 6.4: Beam Quality Information In-Air and With Bismuth Shield](table)

51
This data was inputted into Report 78 Spectrum Processor© (IPEM 1997) to populate the spectra in-air and after exiting the Bismuth shield. The in-air spectra is displayed in Figure 6.14; the beam spectra after exiting the Bismuth shield is displayed in Figure 6.15.

From Figures 6.14 and 6.15, it can be seen that the effective energy of the beam increases from 62.7 keV to 67.7 keV after passing through the Bismuth shield. This data confirms the beam hardening effect of using the Bismuth shield.

Figure 6.14: GE VCT In-Air Spectra

Figure 6.15: Spectra After Exiting Bismuth Shield
### Appendix A

<table>
<thead>
<tr>
<th>Raw Collar Badge Reading (mrem)</th>
<th>EDE 2 (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49</td>
<td>3</td>
</tr>
<tr>
<td>106</td>
<td>4</td>
</tr>
<tr>
<td>245</td>
<td>9</td>
</tr>
<tr>
<td>442</td>
<td>17</td>
</tr>
<tr>
<td>91</td>
<td>3</td>
</tr>
<tr>
<td>889</td>
<td>55</td>
</tr>
<tr>
<td>675</td>
<td>27</td>
</tr>
<tr>
<td>124</td>
<td>9</td>
</tr>
<tr>
<td>327</td>
<td>14</td>
</tr>
<tr>
<td>238</td>
<td>9</td>
</tr>
<tr>
<td>271</td>
<td>10</td>
</tr>
<tr>
<td>914</td>
<td>77</td>
</tr>
<tr>
<td>74</td>
<td>2</td>
</tr>
<tr>
<td>573</td>
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Bibliography


[8] Introduction to the MOSFET Dosimeter. Best Medical Canada, 413 March Road, Ottawa, Ontario, K2K 0E4, Canada.


