An Evaluation and Comparison of Beam Characteristics, Stray Radiation Room Surveys, Organ Dose, and Image Quality of Multiple Intra-Operative Imaging Devices for Orthopedic Lumbar Spinal Surgery

by

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Duke University

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

2015
ABSTRACT

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Abstract

Purpose:

The overall purpose of this study was a comparison of radiation exposure for patients and staff during intra-operative imaging for orthopedic lumbar spine surgery. In order to achieve this, we: (1) Characterized each x-ray machine for physics performance, (2) Measured occupational radiation exposure inside the surgical suite for multiple intra-operative imaging devices utilizing currently in place clinical protocols for abdominal/spinal imaging, and (3) Measured specific organ doses for a phantom of three different Body Mass Indices (BMI) for each machine. We also compared the dose changes relative to changes in BMI as well as surgical image quality changes relative to BMI. This served as the majority of the first phase of a two phase project. The purpose of the second phase of the project will be to optimize scan parameters for surgical hardware placement in terms of image quality and organ dose for the devices that allow for modifications of scanner settings.

Materials and Methods:

(1) X-Ray quality control meters were used to verify particular beam characteristics and additional information was calculated from the beam data. Both a small volume ionization chamber as well as Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) dosimeters were used to validate linear response of new design X-
Ray tubes. (2) Both handheld ionization chamber survey meters as well as Geiger–Muller based personal dose meters were used to measure stray radiation for room surveys in locations representative of typical radiation worker positions during intra-operative imaging. (3) MOSFET dosimeters were placed in an adult male anthropomorphic phantom representing a normal BMI. 20 MOSFETs were used in nine organs with two small volume ion chambers used for skin surface dosimetry. Two additional layers of adipose equivalent material were progressively added to the phantom to represent BMI values of overweight and obese.

Results:

(1) The maximum tube potential, half value layer (HVL), effective energy, and soft tissue f-factor for each machine is as follows: IMRIS VISIUS iCT: 118.4 kVp, 7.66 mm Al, 53.64 keV, and 0.934 cGy/R; Mobis Airo: 122.3 kVp, 7.21 mm Al, 51.31 keV, and 0.925 cGy/R; Siemens ARCADIS Orbic 3D: 83 kVp, 7.12 mm Al, 32.76 keV, and 0.914 cGy/R; GE OEC 9900 Elite: 75 kVp, 4.25 mm Al, 46.6 keV, and 0.920 cGy/R. (2) The highest exposure rates measured during clinically implemented protocols for each scanner are as follows: IMRIS VISIUS iCT: 800 mR/hr; Mobis Airo: 6.47 R/hr; Siemens ARCADIS Orbic 3D: 26.4 mR/hr. (3) The effective dose per scan of each device for a full lumbar spine scan are as follows, for normal, overweight, and obese BMI, respectively: IMRIS VISIUS iCT: 12.00 ± 0.30 mSv, 15.91 ± 0.75 mSv, and 23.23 ± 0.55 mSv; Mobius Airo: 5.90 ± 0.25 mSv, 4.97 ± 0.12
mSv, and 3.44 ± 0.21 mSv; Siemens ARCADIS Orbic 3D: 0.30 ± 0.03 mSv, 0.39 ± 0.02 mSv, 
and 0.28 ± 0.03 mSv; GE OEC 9900 Elite: 0.44 mSv, 0.77 mSv, and 1.14 mSv.

**Conclusion:**

(1) The IMRIS VISIUS iCT i-Fluoro capable CT scanner and Mobius Airo mobile 
CT scanner have similar beam characteristics with significantly different tube parameter 
modulation protocols. Siemens ARCADIS Orbic 3D and GE OEC 9900 offer comparable 
beam characteristics but different imaging methods. All scanners performed within 
factory specifications. (2) The IMRIS VISIUS iCT should not be used in i-Fluoro mode for 
surgical procedures active during scanning due to the 1.42 cGy/s point dose rate in the 
beam field. The high exposure rate from the Mobius Airo is offset by short scan times and 
can be mitigated by ensuring enforcement of currently established radiation protection 
regulations and policies. Minimal stray radiation is measured from the Siemens ARCADIS 
Orbic 3D. (3) The differences in tube modulation of the CT scanners means the Mobius 
Airo offers a significantly reduced effective dose with increasing patient BMI over the 
IMRIS VISIUS iCT. Effective dose from the CT scanners varies as much as one to two 
orders of magnitude higher than the C Arms, but the Siemens ARCADIS Orbic 3D offers 
unusable image quality for patients with higher than normal BMI. Based off of physician 
reported usable surgical image quality of Mobius Airo, this device is recommended for 
continued integration and implementation during routine surgical procedures for 
patients of all BMI in orthopedic lumbar spine surgery.
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1. Introduction to Radiation Dosimetry

Absorbed dose (D) is defined as the energy imparted to matter per unit mass from ionizing radiation and is given in units of gray (Gy) by the following equation [1]:

\[ D \ (\text{Gy}) = \frac{dE}{dm} \left( \frac{J}{kg} \right) \]  \hspace{1cm} (1.1)

where \( E \) is energy in Joules (J) and \( m \) is mass in kilograms (kg).

Occupational absorbed dose must be monitored and has regulatory set limitations on annual accumulation. Based off of National Council on Radiation Protection and Measurements (NCRP) recommendations, the United States Nuclear Regulatory Commission’s (U.S.NRC) current annual occupational dose limit is 50 mSv [2]. The unit of sievert (Sv) is used for equivalent dose (H\(_R\)), which modifies absorbed dose by a radiation weighting factor (W\(_R\)), determined from the relative biological effectiveness (RBE) of the type of incident ionizing radiation. Table 1.1 below displays the relationship between types of ionizing radiation and their corresponding W\(_R\) according to the most recent relevant International Commission on Radiological Protection (ICRP) report, Report 103, published in 2007 [3]. Our study only involves ionizing radiation from x-ray emitters in the diagnostic energy range.
Table 1.1: Radiation Weighting Factors, $W_R$ (ICRP 103, 2007)

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Radiation Weighting Factor, $W_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma/X-Rays, electrons, muons</td>
<td>1</td>
</tr>
<tr>
<td>Protons, charged pions</td>
<td>2</td>
</tr>
<tr>
<td>Alpha particles, fission products, heavy ions</td>
<td>20</td>
</tr>
<tr>
<td>Neutrons</td>
<td>Continuous function</td>
</tr>
</tbody>
</table>

Equivalent dose can further be modified by specific tissue weighting factors ($W_T$) for organs throughout the body, which can then be summed to determine an overall whole body effective dose ($H$), also measured in Sv. Table 1.2 displays the $W_T$ values from ICRP Report 103 that were used throughout this study [3].

Table 1.2: Tissue Weighting Factors, $W_T$ (ICRP 103, 2007)

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$W_T$</th>
<th>$\sum W_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone-marrow (red), colon, lung, stomach, breast, remaining tissue*</td>
<td>0.12</td>
<td>0.72</td>
</tr>
<tr>
<td>Gonads</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Bladder, esophagus, liver, thyroid</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Bone surface, brain, salivary glands, skin</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphnodes, muscle, oral mucosa, pancreas, prostate (♂♂), small intestine, spleen, thymus, uterus/cervix (♀♀)

The relationship between absorbed dose, equivalent dose, and effective dose are characterized by Figure 1.1 below.
Ionization chambers, or ion chambers, are the most widely used gas-filled radiation detectors. Ion chambers measure charge in coulombs (C) liberated per mass (kg) of air by ionizing radiation as it travels through the chamber. The units of C/kg are analogous to the standard unit of exposure, roentgen (R), through the following equation:

\[ 1 \, R = 2.58 \times 10^{-4} \, \frac{C}{kg} \]  

(1.2)

As photons travel through the chamber and liberate ion pairs throughout the gas, a potential is applied across the anode-cathode inside the chamber. This potential generates a current that is proportional to the number of ion pairs liberated by the...
radiation [4]. Using the specific ionization of the gas inside the chamber of known volume and density, the relationship between charge and energy can be calculated. If the chamber is filled with air, which has a specific ionization, $W$, of 33.97 eV per ion pair, the relationship is:

$$33.97 \text{ eV per ion pair} \times \frac{1.602 \times 10^{-19}}{\text{eV per C}} = 33.97 \frac{J}{C}$$

From this relationship, the exposure generated by gamma and x-rays of less than 3 MeV energy can be used to calculate the absorbed dose of incident ionizing radiation in the same medium by the following calculation:

$$1 R = 2.58 \times 10^{-4} \frac{C}{kg} \times 33.97 \frac{J}{C} = 0.876 \text{ cGy}$$

### 1.2 Metal Oxide Semiconductor Field Effect Transistor

Metal oxide semiconductor field effect transistors (MOSFET) are validated for use in radiation dosimetry as integrating dosimeters for gamma/x-ray exposure and various electron modalities [5]. As dosimeters, they have several advantages, such as being dose rate and temperature independent as well as isotropic (±2% for 360°) [6].

Operationally, a large negatively biased voltage is applied at a polycrystalline silicon gate between positively biased source and drain terminals. This induces a large number of electron holes to migrate from a negatively doped silicon substrate to an
oxide-silicon interface, creating a conduction channel between the source and the drain and allowing for the flow of current [7].

Ionizing radiation produces electron-hole pairs in the silicon substrate, which move to the oxide-silicon interface where they become trapped, causing a negative permanent threshold shift in voltage ($\Delta V_{TH}$) [7]. Measuring this permanent change in voltage allows a corresponding dose to be determined by utilizing an established conversion factor. This conversion factor is determined by comparing the voltage shift with a dose from a calibrated dosimeter, most often an ion chamber, when both devices are simultaneously placed in the same beam of ionizing radiation, giving units of dose per volt (mGy/mV).

1.3 Piranha 557 X-Ray Quality Control Meter

RTI Electronics AB (Molndal, Sweden) Piranha 557 X-ray quality control device measures X-ray beam quality by determining peak tube potential (kVp), total filtration (TF) of the complete system (mm Al), as well as the first half-value layer (HVL) of the device (mm Al). The detector wirelessly communicates via Bluetooth technology with a handheld digital readout. Throughout the diagnostic x-ray range (35-155 kV), the Piranha readings are accurate to ±1.5% [8]. An example of Piranha placement can be seen in Figure 2.2.
1.4 RadEye G Personal Dose Rate Meter

ThermoScientific, Inc.’s (Erlangen, Germany) RadEye™ G Personal Dose Rate Meter utilizes a Geiger-Mueller detector in order to measure exposure rates as low as 0.05 µSv/hr (5 µR/hr) and as high as 0.1 Sv/hr (10 R/hr) [9]. Each detector is capable of recording nearly 1600 data points at a programmable time interval, and each data point consists of the maximum and mean exposure rate during each time interval. An example of a RadEye is given below in Figure 1.2.

![RadEye G Personal Dose Rate Meter](image)

Figure 1.2: ThermoScientific, Inc. RadEye™ G Personal Dose Rate Meter

1.5 PCXMC

PCXMC (Version 2.0.1.2) is a Monte Carlo (MC) based simulation software package created and published by the Radiation and Nuclear Safety Authority (STUK;
Helsinki, Finland) that allows specific organ dose calculation for planar and fluoroscopic x-ray imaging devices. From the resultant simulation data, it is also capable of calculating effective dose for multiple ICRP report guidelines, as well as Risk of Exposure Induced Death (REID). It utilizes a scalable mathematical model based off reference man height and mass to vary patient size, age group, and gender. It requires accurate input of beam parameters, including spectrum characteristics, field size, and field position. Utilizing one of a variety of inputs based on machine outputs, such as incident air kerma (mGy), Dose-Area Product (DAP) (mGy·cm²), entrance exposure (mR), or current-time product (mA·s). An example of the input interface is shown in Figure 1.3 below.

Figure 1.3: Example PCXMC Simulation Interface
2. Tube Potential Accuracy and Tube Current Linearity Validation and Troubleshooting of Siemens STRATON X-Ray Tube

2.1 Introduction

Gathering initial information for x-ray beam characteristics on medical imaging devices is necessary for proper quality control. In order to conduct accurate quality control on diagnostic x-ray devices in a timely manner, a multifunction x-ray quality control meter is implemented to measure the peak tube potential. While tube current across the anode cannot be empirically measured at a point in the beam, it is also necessary to determine that the appropriate changes in console settings for tube current are accurately reflected in the scanner. This correlation can be established by measuring the dose rate linearity of a detector within the beam throughout the range of selectable tube current settings of the device.

The IMRIS VISIUS iCT system utilized in the orthopedic surgery suite of Duke Medicine Pavilion (DMP) utilizes a Siemens STRATON x-ray tube for both traditional and fluoroscopic studies. The Siemens Medical Solutions STRATON x-ray tube deviates from traditional rotating anode tube design by being the first in a class of rotating envelop tubes, where the entire tube rotates in relation to the fixed anode axis [10]. The STRATON is also manufactured with a higher level of inherent infiltration than other previous Siemens tubes. These two features together can present difficulties when
utilizing traditional quality control measurement devices. Initial quality control testing of the IMRIS VISIUS iCT with two different Piranha meters yielded a significant deviation of measured tube voltage from machine indicated peak tube potential. Both IMRIS and Siemens field engineers were on site throughout the week of initial testing, and both engineers reported that deviations in actual versus measured maximum tube potential of up to 10% are considered nominal in their tubes. Because dose absorbed from diagnostic x-ray procedures is proportional to the square of tube potential and is significant for clinical image quality, further investigation was necessary.

Figure 2.1: IMRIS VISIUS iCT
2.2 Materials and Methods

2.2.1 Tube Voltage Determination

RTI Electronics AB (Molndal, Sweden) Piranha 557 (S/Ns: CB2-08090150, CB2-08080027; calibrated: 12/03/2014, 08/2009) x-ray quality control meters were placed in the beam of an IMRIS VISIUS iCT and the meter was set for traditional Siemens x-ray tube calibration factors. Radiochromic film was placed under the meter for the purpose of verifying that the detector portion of the meter was within the field of the scanner, as shown in Figure 2.2. The CT was operated in planar scan mode with fixed tube location, a maximum tube potential of 120 kVp, a scan time of 1 second, and an initial tube current of 100 mA. The results from the Piranha were logged. Feedback from the Piranha is instantaneous and, after initial readings were significantly high, the scan parameters were adjusted to a maximum tube potential of 100 kVp, which also measured significantly high. To confirm the readings, the second Piranha was used under the original scan parameters and also read high.
In order to validate the proper function and calibration of both Piranha meters, they were taken to a Precision X-ray Inc. (PXI) XRAD 320 x-ray irradiator. Utilizing the Piranha’s “w/ 3mm Al” calibration factor and matching F4 filter for the irradiator, both Piranha’s were irradiated in a 20x20cm field at 12.5 mA for 2 seconds with tube potential varied from 50 to 130 kVp in 20 kVp increments as well as 140 kVp. When the percentage difference of the indicated and measured tube potential was within acceptable standards during the PXI XRAD 320 irradiations, further trouble shooting of the issue was investigated by conducting Piranha measurements on two additional imaging devices, a Siemens SOMATOM Definition Flash, which utilizes the same Siemens STRATON x-ray tube in its construction as the IMRIS VISIUS iCT, as well as a GE Lightspeed VCT scanner. The GE scanner based scanner measured within
acceptable percent difference, but again the Siemens STRATON based scanner measured significantly higher.

Having narrowed down the most likely point of origin of the source of the significant deviation to the Siemens STRATON tube, RTI Elections AB headquarters was contacted directly. The research team was informed that the measured difference is a known issue with Piranha meters on STRATON tubes. An updated firmware was available by sending the meter directly to the manufacturer. Upon receiving both returned meters from RTI with updated calibration factors available and renewed calibrations, the scan parameters were repeated for both Siemens SOMATOM Definition Flash and IMRIS VISIUS iCT scanners and were within acceptable standards. Field engineers for both IMRIS and Siemens were unaware of any known issue with the meters.

### 2.2.2 Tube Current Linearity

The fluoroscopic mode of the IMRIS VISIUS iCT was utilized to investigate the linearity of different tube current settings of the scanner. A 0.18cc ion chamber (Model 10x5-0.18, RadCal, Monrovia, CA) connected to a monitor (Model 9015, RadCal) was placed on the skin surface of a CIRCS (Norfolk, VA) Model 701-D adult male anthropomorphic phantom along the lumbar spine. A single calibrated MOSFET detector was placed adjacent to the ion chamber.
Figure 2.3: Ion Chamber and MOSFET Detector Placement

Six scan protocols were utilized across the same operational peak tube potential setting and time per tube rotation for approximately the same length of fluoroscopic study and are displayed in Table 2.1.

Table 2.1: Scan Parameters for Tube Current Linearity

<table>
<thead>
<tr>
<th>Setup</th>
<th>Tube Potential (kVp)</th>
<th>Tube Rotation/s</th>
<th>mAs/rotation</th>
<th>Scan time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120</td>
<td>0.36</td>
<td>60</td>
<td>15.44</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>0.36</td>
<td>50</td>
<td>15.06</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>0.36</td>
<td>40</td>
<td>14.70</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>0.36</td>
<td>30</td>
<td>14.50</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>0.36</td>
<td>20</td>
<td>15.22</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>0.36</td>
<td>10</td>
<td>16.28</td>
</tr>
</tbody>
</table>

Because diagnostic x-ray equipment emits a spectrum of x-rays at various energies through the entire range of its maximum tube potential, a mono-energetic effective energy must be determined for use in beam quality calculations. The measured
HVL, along with information from the manufacturer and SpekCalc beam spectrum simulation software [11] [12], was used to determine the effective energy of the beam at the peak tube potential of 120 kVp.

Expanding Equation 1.4 for absorbed dose in the same medium of a measured exposure, it is possible to relate the absorbed dose measured in one medium to that of another. This can be done by determining an f-factor, which relates the mass attenuation absorption coefficient of the two medium at the same energy. Utilizing the effective energy to determine the mass absorption attenuation coefficients for both dry air and soft tissue from National Institute of Standards and Technology (NIST) tables [13], an f-factor was calculated using the following formula [14]:

$$ f = 0.876 \times \frac{(\mu_{en}/\rho)_{soft\ tissue}}{(\mu_{en}/\rho)_{air}} $$

(2.1)

In addition to the proper energy dependent correction factor applied to the ion chamber reading, the f-factor was applied to both ion chamber and MOSFET doses in order to calculate an absorbed dose in soft tissue for each scan parameter. The absorbed doses were then normalized to time in order to account for slight variations in exposure time and give absorbed dose rates.

Similarly, to confirm the tube current linearity on the Siemens STRATON tube utilized in the Siemens SOMATOM Definition Flash, the same Rad Cal 9015 electrometer
was used, this time with the 0.18cc ion chamber placed in the center of a 32cm x 15cm CTDI body phantom. Seven different 1 second long scans were conducted with various fixed tube current settings throughout scanner’s selectable range. The exposure rate readings from the calibration factor corrected ion chamber were recorded and analyzed.

### 2.2.3 Analytical Formula Used

Formula 2.2 below outlines the standard formula for percentage error used to compare the expected and measured values for peak tube voltage.

\[
Percentage\ Error = \left| \frac{Expected\ Value - Actual\ Value}{Expected\ Value} \right| \times 100
\]  

(2.2)

### 2.3 Results

#### 2.3.1 Tube Potential Measurements

The results from the initial peak tube potential measurements from the IMRIS VISIUS iCT are displayed in Table 2.2. As shown below, the percent difference between the console setting and the Piranha measured values for both meters varies between 5 – 8.5%, which is enough variation to cause concern.
Table 2.2: Initial Peak Tube Potential Measurements, IMRIS VISIUS iCT  
(05/05/2014 – 05/06/2014)

<table>
<thead>
<tr>
<th>Piranha S/N</th>
<th>Tube Potential Setting (kVp)</th>
<th>Peak Tube Voltage (kVp)</th>
<th>Percentage Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0027</td>
<td>120</td>
<td>130.1</td>
<td>8.42%</td>
</tr>
<tr>
<td>0027</td>
<td>100</td>
<td>105.0</td>
<td>5.00%</td>
</tr>
<tr>
<td>0150</td>
<td>120</td>
<td>129.3</td>
<td>7.75%</td>
</tr>
<tr>
<td>0027</td>
<td>120</td>
<td>129.8</td>
<td>8.17%</td>
</tr>
</tbody>
</table>

Table 2.3 below reflects the measurements taken for various tube potential settings on the PXI XRAD 320 irradiator, along with the TF and HVL. Table 2.4 shows the calculated percentage error for the peak tube voltage measurements for each Piranha. All of the values measured for the XRAD 320 were within 2% of the machine indicated settings.

Table 2.3: PXI XRAD 320 Piranha Measurements (07/11/2014)

<table>
<thead>
<tr>
<th>kVp Setting</th>
<th>kVp measurement</th>
<th>TF (mm)</th>
<th>HVL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>50.45</td>
<td>50.90</td>
<td>8.0</td>
</tr>
<tr>
<td>70</td>
<td>70.63</td>
<td>70.83</td>
<td>7.6</td>
</tr>
<tr>
<td>90</td>
<td>89.72</td>
<td>90.13</td>
<td>7.7</td>
</tr>
<tr>
<td>110</td>
<td>108.2</td>
<td>109.8</td>
<td>7.8</td>
</tr>
<tr>
<td>130</td>
<td>128.4</td>
<td>129.2</td>
<td>7.6</td>
</tr>
<tr>
<td>140</td>
<td>137.5</td>
<td>138.5</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Table 2.4: Percentage Error from XRAD 320 Piranha Measurements

<table>
<thead>
<tr>
<th>kVp</th>
<th>0150</th>
<th>0027</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.90%</td>
<td>1.80%</td>
</tr>
<tr>
<td>70</td>
<td>0.90%</td>
<td>1.19%</td>
</tr>
<tr>
<td>90</td>
<td>0.31%</td>
<td>0.14%</td>
</tr>
<tr>
<td>110</td>
<td>1.64%</td>
<td>0.18%</td>
</tr>
<tr>
<td>130</td>
<td>1.23%</td>
<td>0.62%</td>
</tr>
<tr>
<td>140</td>
<td>1.79%</td>
<td>1.07%</td>
</tr>
</tbody>
</table>

Listed in Table 2.5 are the measured values from the GE Lightspeed VCT system utilizing GE’s 7° anode calibration factor selection in the Piranha’s settings. Table 2.6 lists the corresponding percentage error calculation for the peak tube potential. As with the values for the XRAD 320, all measurements are within 2% of the expected value. Table 2.7 lists the measurements for the Siemens SOMATOM Definition Flash, utilizing the same STRATON tube from the VISIUS iCT, and the standard Siemens tube settings in the Piranha. Likewise, Table 2.8 shows the percentage different. Like the VISIUS iCT, the percentage error is greater than the 2% acceptable margin from the expected values.

Table 2.5: GE Lightspeed VCT Piranha Measurements (07/14/2014)

<table>
<thead>
<tr>
<th>kVp Setting</th>
<th>kVp Measurement</th>
<th>TF (mm)</th>
<th>HVL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0150</td>
<td>0027</td>
<td>0150</td>
</tr>
<tr>
<td>80</td>
<td>79.16</td>
<td>79.08</td>
<td>9.9</td>
</tr>
<tr>
<td>100</td>
<td>98.29</td>
<td>98.36</td>
<td>9.7</td>
</tr>
<tr>
<td>120</td>
<td>118.1</td>
<td>118.3</td>
<td>9.6</td>
</tr>
<tr>
<td>140</td>
<td>137.1</td>
<td>137.8</td>
<td>9.6</td>
</tr>
</tbody>
</table>
Table 2.6: Percentage Error from GE Discovery CT Piranha Measurements

<table>
<thead>
<tr>
<th>kVp</th>
<th>0150</th>
<th>0027</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>1.05%</td>
<td>1.15%</td>
</tr>
<tr>
<td>100</td>
<td>1.71%</td>
<td>1.64%</td>
</tr>
<tr>
<td>120</td>
<td>1.58%</td>
<td>1.42%</td>
</tr>
<tr>
<td>140</td>
<td>2.07%</td>
<td>1.57%</td>
</tr>
</tbody>
</table>

Table 2.7: Siemens SOMATOM Definition Flash Piranha Measurements (07/14/2014)

<table>
<thead>
<tr>
<th>kVp Setting</th>
<th>kVp measurement</th>
<th>TF (mm)</th>
<th>HVL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0150 0027</td>
<td>0150 0027</td>
<td>0150 0027</td>
<td>0150 0027</td>
</tr>
<tr>
<td>80</td>
<td>79.71</td>
<td>79.21</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.63</td>
</tr>
<tr>
<td>100</td>
<td>97.59</td>
<td>96.87</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.66</td>
</tr>
<tr>
<td>120</td>
<td>116.2</td>
<td>115.0</td>
<td>9.7</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>7.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.60</td>
</tr>
<tr>
<td>140</td>
<td>133.8</td>
<td>132.3</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.41</td>
</tr>
</tbody>
</table>

Table 2.8: Percentage Error from Siemens SOMATOM Definition Flash Piranha Measurements

<table>
<thead>
<tr>
<th>kVp</th>
<th>0150</th>
<th>0027</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0.36%</td>
<td>0.99%</td>
</tr>
<tr>
<td>100</td>
<td>2.41%</td>
<td>3.13%</td>
</tr>
<tr>
<td>120</td>
<td>3.17%</td>
<td>4.17%</td>
</tr>
<tr>
<td>140</td>
<td>4.43%</td>
<td>5.50%</td>
</tr>
</tbody>
</table>

After the Piranha meters were returned from RTI, Table 2.9 reflects the post-firmware update measurements from the IMRIS VISIUS iCT for Piranha S/N CB2-08080027, and Table 2.10 shows the calculated percentage error. The measurements throughout the maximum tube potential range for the scanner were all within 2% of the expected value, which is within acceptable tolerances.
Table 2.9: IMRIS VISIUS iCT Piranha Measurements (09/26/2014)

<table>
<thead>
<tr>
<th>kVp Setting</th>
<th>S/N: 0027</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kVp</td>
</tr>
<tr>
<td>80</td>
<td>80.18</td>
</tr>
<tr>
<td>100</td>
<td>98.75</td>
</tr>
<tr>
<td>120</td>
<td>118.4</td>
</tr>
<tr>
<td>140</td>
<td>137.4</td>
</tr>
</tbody>
</table>

Table 2.10: Percentage Error from IMRIS VISIUS iCT Piranha Measurements

<table>
<thead>
<tr>
<th>kVp Setting</th>
<th>Measured kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0.23%</td>
</tr>
<tr>
<td>100</td>
<td>1.25%</td>
</tr>
<tr>
<td>120</td>
<td>1.33%</td>
</tr>
<tr>
<td>140</td>
<td>1.86%</td>
</tr>
</tbody>
</table>

2.3.2 Tube Current Linearity

Initial test recordings were based off the standard CT input of selecting tube current (mA) at the desired tube potential setting. However, when a technician operates the IMRIS VISIUS iCT, he or she is actually selecting the product of tube current and exposure time per rotation (mAs/rotation). The console also displays tube rotation time in used of tube rotations per second rather than the more common seconds per tube rotation. The DICOM information readout for the presumed tube current in the images of test scans reported a tube current value of a 2.8 times higher than expected based off the console setting.
For Siemens software, the three DICOM tags, which represent “effective mAs” or “mAs/rotation”, “mA”, and “time per rotation” are “Exposure,” “X-rayTubeCurrent,” and “ExposureTime,” respectively as shown in Figure 2.4.

Table 2.11 below shows the measurements and subsequent calculations for ion chamber reading (Rdg) to absorbed dose for corresponding scan parameters from Table 2.1. Similarly, Table 2.12 shows the MOSFET measured absorbed dose as well as dose rate calculation for each parameter.
Table 2.11: Ion Chamber Dose Rate Calculations

<table>
<thead>
<tr>
<th>Setup</th>
<th>Ion Chamber (Rdg)</th>
<th>Calibration Factor</th>
<th>f-factor (cGy/R)</th>
<th>Dose Rate (cGy/s)</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.877</td>
<td>0.941 R/Rdg</td>
<td>3.648</td>
<td>3.407</td>
<td>0.221</td>
</tr>
<tr>
<td></td>
<td>0.038</td>
<td></td>
<td></td>
<td></td>
<td>0.002</td>
</tr>
<tr>
<td>5</td>
<td>7.259</td>
<td>0.934</td>
<td>6.380</td>
<td>6.831</td>
<td>0.424</td>
</tr>
<tr>
<td></td>
<td>0.341</td>
<td></td>
<td></td>
<td></td>
<td>0.023</td>
</tr>
<tr>
<td>4</td>
<td>10.435</td>
<td>0.460</td>
<td>9.171</td>
<td>9.819</td>
<td>0.624</td>
</tr>
<tr>
<td></td>
<td>0.134</td>
<td></td>
<td></td>
<td></td>
<td>0.031</td>
</tr>
<tr>
<td>3</td>
<td>13.540</td>
<td>0.311</td>
<td>11.900</td>
<td>12.741</td>
<td>0.821</td>
</tr>
<tr>
<td></td>
<td>0.67</td>
<td></td>
<td></td>
<td></td>
<td>0.061</td>
</tr>
<tr>
<td>2</td>
<td>17.755</td>
<td>0.134</td>
<td>15.605</td>
<td>16.707</td>
<td>1.025</td>
</tr>
<tr>
<td></td>
<td>0.31</td>
<td></td>
<td></td>
<td></td>
<td>0.009</td>
</tr>
<tr>
<td>1</td>
<td>21.595</td>
<td>0.516</td>
<td>18.980</td>
<td>20.321</td>
<td>1.166</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td>0.032</td>
</tr>
</tbody>
</table>

Table 2.12: MOSFET Absorbed Dose Measurement and Dose Rates

<table>
<thead>
<tr>
<th>Setup</th>
<th>Absorbed Dose (cGy)</th>
<th>Std Dev</th>
<th>Dose Rate (cGy/s)</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.96</td>
<td>0.11</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>7.49</td>
<td>0.67</td>
<td>0.50</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>10.97</td>
<td>1.10</td>
<td>0.75</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
<td>14.55</td>
<td>0.61</td>
<td>1.00</td>
<td>0.04</td>
</tr>
<tr>
<td>2</td>
<td>18.66</td>
<td>0.15</td>
<td>1.23</td>
<td>0.01</td>
</tr>
<tr>
<td>1</td>
<td>23.13</td>
<td>0.11</td>
<td>1.42</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The results from the previous tables were used to plot dose rate (cGy/s) against mAs per tube rotation. Figure 2.5 below displays these plots along with the respective R² value for each fit line. The results show that the linearity with respect to tube current modulation of the IMRIS VISIUS iCT are well within expectations for fluoroscopic use of the Siemens STRATON x-ray tube.
The scan parameters utilized for testing the Siemens SOMATOM Definition Flash scanner along with the measured exposure rate from the ion chamber are listed in Table 2.13 below.

**Table 2.13: Siemens SOMATOM Definition Flash Linearity Measurements**

<table>
<thead>
<tr>
<th>Static</th>
<th>140 kVp</th>
<th>270° Tube Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup</td>
<td>mA</td>
<td>Time (s)</td>
</tr>
<tr>
<td>1</td>
<td>500</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>1.000</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>1.000</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>1.000</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>1.000</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>1.000</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Figure 2.5: IMRIS VISIUS iCT Tube Current Linearity
Figure 2.6 below shows a plot of ion chamber measured exposure rate versus tube current for the SOMATOM Definition Flash, along with a fit line and associated $R^2$ value. The fit of the values shows that the STRATON tube within the Definition Flash in conventional CT mode performs with optimum tube current linearity.

![Figure 2.6: Siemens SOMATOM Definition Flash Linearity](image)

### 2.4 Conclusion

Initial measurements of the IMRIS VISIUS iCT beam quality with two different multifunction x-ray meters yielded a deviation of ~8% from machine indicated peak tube potential. At the time of determination, both Siemens and IMRIS field engineers stated that they consider any deviation of tube voltage within 10% of the nominal peak tube voltage to be considered acceptable. Understanding the exponential relationship between tube potential and patient absorbed dose warranted further investigation.
Coordinating and facilitating the communication between a German x-ray tube manufacturer, a Swedish quality control meter manufacturer, and an American imaging device assembly company proved that a simple but true answer existed to solve an obvious issue.

The manufacturer’s recommended setting is 60 mAs/rotation for CT i-Fluoro mode. While Figure 2.6 does show that the linearity of the tube is also well within normal parameters, it also highlights that at the recommended setting of 60 mAs/rotation, the peak absorbed dose rate along the patient’s skin is as high as 1.4 cGy/s. While utilizing CT i-Fluoro mode, most scans only occur on the order of seconds. However, the physician is entirely in control of the duration of scan, and in the event that a scan runs long, significant dose to the patient and operator can be accumulated. As the IMRIS VISIUS iCT was designed specifically to be used intra-operatively, if a continuous scan were to be performed by a surgeon whose hands were in the useful field of the beam, significant absorbed dose would be accumulated. The high dose rate within the field of the beam also served to highlight the need for additional validation of the scanner’s stray radiation characteristics.
3. Stray Radiation Room Survey Evaluation

3.1 Introduction

For x-ray emitting medical devices, be it plane radiograph, traditional CT, or fluoroscopy, the only federal regulation that governs the maximum output of stray radiation is 21 CFR 1020.30, which, under the enforcement of the Federal Drug Administration (FDA), limits leakage at one meter in any direction from the source to 100 mR in 1 hour prior to the device leaving the manufacturer’s assembly plant and does not differentiate between tube housings, fluoroscopic assemblies, spot film, or CT systems in this regard [15]. Within the state of North Carolina 10A NCAC 15.0600 governs compliance with diagnostic medical x-ray devices, including fluoroscopy, which similarly is limited to 100 mR/hr at 1 meter. [16]. As long as the leakage technique factor of a device passes this standard, the entire unit may be installed and operated clinically. Because multi-use devices are categorized by their primary function, the additional modes are not tested in the leakage technique factor. Thus, a CT scanner that also has fluoroscopic capabilities must only pass the leakage technique factor for CT use. However, the development of conventional CT scanners that also have fluoroscopic capabilities has given rise to concerns over stray radiation to patients and clinicians that routinely utilize these devices. Specifically, clinicians are subject to repeated exposures per procedure. It is thus necessary to determine the stray radiation rates that scanners
are capable of emitting and ensure that appropriate education and control measures are in place for medical personal that will be utilizing these sources of higher stray radiation. It is also essential to conduct a room survey to determine dose rates throughout the room in the even that a dose reconstruction becomes necessary.

3.2 Stray Radiation of Siemens STRATON X-Ray Tube in Conventional and Fluoroscopic Use

3.2.1 Materials and Methods

Metering of the Siemens STRATON tube begin with the IMRIS VISIUS iCT. Maximum stray radiation dose rate in $\mu$Gy/mAs is indicated by Siemens in the system operator’s manual for each device. The data is organized into a coordinate system (intersection of scanner axis with scan plane) around the center of the scanner bore for the horizontal and vertical planes [17]. Figure 3.1 below reflects these factory maximum values for the vertical plane of the scanner. Values from the table will be compared to measured stray radiation rates.
A standard polymethyl methacrylate (PMMA) CTDI_{vol} Phantom, 32cm diameter x 15 cm length, was centered in the scan plane for the stray radiation survey as illustrated in Figure 3.2. The scans are conducted in accordance with the manufacturer’s specified settings for maximum tube voltage and maximum total collimation width during a single center slice rotation axial scan [17]. The specific scan parameters are shown in Table 3.1 below.
Figure 3.2: 32cm x 15cm CTDI Phantom Placement for Stray Radiation Survey

Table 3.1: Stray Radiation Survey Scanner Settings

<table>
<thead>
<tr>
<th>Scan Parameters - Service Mode - Axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation Time:</td>
</tr>
<tr>
<td>Slice Collimation:</td>
</tr>
<tr>
<td>Rotation #:</td>
</tr>
<tr>
<td>DOM Type:</td>
</tr>
<tr>
<td>Region:</td>
</tr>
<tr>
<td>Voltage:</td>
</tr>
<tr>
<td>Current:</td>
</tr>
<tr>
<td>mAs:</td>
</tr>
<tr>
<td>Power:</td>
</tr>
<tr>
<td>X-Ray:</td>
</tr>
<tr>
<td>Rot Anode:</td>
</tr>
<tr>
<td>Offset Correction:</td>
</tr>
<tr>
<td>Adaptive Filter (DMS):</td>
</tr>
<tr>
<td>Focus:</td>
</tr>
<tr>
<td>Emission Control:</td>
</tr>
<tr>
<td>DMS Data Pattern:</td>
</tr>
</tbody>
</table>
After positioning the CTDI phantom, a tape measure was used to measure linear distance from the center of the phantom in the position it would be scanned. Distances of 1, 2, and 3 meters were marked in line with the patient couch in both the front and back of the scanner. Two hand held survey meters, Fluke Biomedical 451P Ion Chambers (S/Ns: 2973, 1676; calibrated: 03/12/2014, 03/13/2014) were held in each position at the same height as the center of the phantom during a scan. Each scan was performed three times and the metered accumulated exposure in roentgens for each position was recorded. These values were averaged and then used for calculation of the normalized exposure rate.

Siemens SOMATOM Definition AS System Owner’s Manual calls for 500 cm\(^3\) ion chamber to be used. Stray radiation survey of Siemens VISIUS was conducted with Fluke Biomedical 451P Pressurized \(\mu\)R Ion Chamber Radiation Survey Meters with 230 cc volume pressurized air.

Following the survey conducted on the IMRIS VISIUS iCT, the same procedure was repeated for a Siemens SOMATOM Definition Flash located in the Duke Cancer Center. The ratio of the measured exposure to the factory data was used to determine acceptable performance limits of scatter radiation production.

Because the scan parameters for the manufacturer’s acceptance testing is not relevant to clinically used protocols, it is necessary to conduct further testing on scatter
radiation throughout the operating room as the scanner is designed for intra-operative use. In order to gain knowledge of dose rates throughout the room in common locations that radiation workers may stand, the same hand held survey meters were used in specific locations to measure exposure rate for three common protocols established for the scanner. CIRS Model 701-D phantom was utilized during scanning to provide realistic scatter radiation from patient imaging.

The first standard protocol used was conducted for a CT head scan, which consisted of a tube potential of 120 kVp, tube current of 270 mA, 1.0 tube rotation per second, a scanner pitch of 0.55 through a 20 cm scan length taking 16.29 seconds of total time. Exposure rates were measured from three different positions described in Table 3.4, which share the first three locations detailed in both Figure 3.3 and Figure 3.4 below.

The second standard protocol applies to the intra-operative use of CT i-Fluoro for orthopedic spinal surgery. It corresponds to the scan settings from Setup 1 in Table 2.1. Measurements for 10 different locations shown in Figure 3.3 below and described in Table 3.5 were recorded.
The third and final protocol tested was for a standard CT Chest/Abdomen/Pelvis (C/A/P) scan at a tube potential of 120 kVp, tube current of 200 mA, 0.5 tube rotation per second, a scanner pitch of 0.55, and a 39.2 cm scan length. The locations surveyed throughout the operating room are labelled in Figure 3.4 and described in Table 3.6.
3.2.1.1 Formula used

Dose in air (mGy) from measured accumulated exposure (R):

\[ D_{\text{air}} (\text{mGy}) = 0.869 \left(\frac{\text{mgY}}{R}\right) \times X (R) \]  \hspace{1cm} (2.3)

Stray radiation in micro gray (µGy) per mAs (64-slice, Open 64-slice):

\[ D_{\text{air}} (\text{µGy/mAs}) = \frac{D_{\text{air}} (\text{mGy})}{\text{500 effective mAs}} \times 1000 \text{ (µGy/mGy)} \]  \hspace{1cm} (2.4)

Factor of difference of company data versus measured:

\[ \frac{D_{\text{air}} (\text{µGy/mAs})}{\text{Company Data (µGy/mAs)}} \]  \hspace{1cm} (2.5)
3.2.2 Results

For the IMRIS VISIUS iCT, Table 3.2 below includes the accumulated exposure recordings for five different positions along the scanner centerline at varying distances on both the table-side and back-side. The exposure is converted to dose in air and subsequently normalized per mAs for direct comparison to the company data available in the Siemens SOMATOM Definition AS System Owner Manual.

Table 3.2: IMRIS VISIUS iCT Stray Radiation Survey Results (05/07/2015)

<table>
<thead>
<tr>
<th>Distance</th>
<th>Position</th>
<th>X (R)</th>
<th>$D_{air}$ (mGy)</th>
<th>$D_{air}$ (uGy/mAs)</th>
<th>Factory Data (uGy/mAs)</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m</td>
<td>Table-side</td>
<td>0.00200</td>
<td>0.01738</td>
<td>0.0348</td>
<td>0.0855</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Back-side</td>
<td>0.00198</td>
<td>0.01721</td>
<td>0.0344</td>
<td>0.0890</td>
<td>0.4</td>
</tr>
<tr>
<td>2m</td>
<td>Table-side</td>
<td>0.00056</td>
<td>0.00487</td>
<td>0.0097</td>
<td>0.0218</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Back-side</td>
<td>0.00072</td>
<td>0.00626</td>
<td>0.0125</td>
<td>0.0244</td>
<td>0.5</td>
</tr>
<tr>
<td>3m</td>
<td>Table-side</td>
<td>0.00026</td>
<td>0.00226</td>
<td>0.0045</td>
<td>0.0086</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Back-side</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

Similarly, the results for the Siemens SOMATOM Definition Flash are displayed in Table 3.3.
Table 3.3: Siemens SOMATOM Definition Flash Radiation Survey Results
(06/09/2014)

<table>
<thead>
<tr>
<th>Distance</th>
<th>Position</th>
<th>X (R)</th>
<th>D\textsubscript{air} (mGy)</th>
<th>D\textsubscript{air} (uGy/mAs)</th>
<th>Factory Data (uGy/mAs)</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>Table-side</td>
<td>0.00198</td>
<td>0.0172</td>
<td>0.0344</td>
<td>0.0855</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Back-side</td>
<td>0.00188</td>
<td>0.0163</td>
<td>0.0327</td>
<td>0.0890</td>
<td>0.4</td>
</tr>
<tr>
<td>2 m</td>
<td>Table-side</td>
<td>0.00101</td>
<td>0.0088</td>
<td>0.0176</td>
<td>0.0218</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Back-side</td>
<td>0.00088</td>
<td>0.0077</td>
<td>0.0153</td>
<td>0.0244</td>
<td>0.6</td>
</tr>
<tr>
<td>3 m</td>
<td>Table-side</td>
<td>0.00040</td>
<td>0.0035</td>
<td>0.0070</td>
<td>0.0086</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Back-side</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

In instances for both scanners, a position of 3 meters directly behind the scanner
did not allow for the sensitivity of the survey meter used to reach its minimum
detectable amount or lower limit of detection.

The results of the room survey locations for CT Head, CT i-Fluoro Spine, and CT C/A/P protocols are shown in Table 3.4, and below, respectively.

Table 3.4: CT Head Protocol Scatter Radiation Survey Results

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Exposure Rate (mR/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45° from Gantry @ 1m</td>
<td>440</td>
</tr>
<tr>
<td>B</td>
<td>Behind Shield @ 1m</td>
<td>2.60</td>
</tr>
<tr>
<td>C</td>
<td>Behind Gantry @ 4.35m</td>
<td>77.0</td>
</tr>
</tbody>
</table>
Table 3.5: CT i-Fluoro Spine Protocol Scatter Radiation Survey Results

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Exposure Rate (mR/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A – 45° from Gantry @ 1m</td>
<td>800</td>
</tr>
<tr>
<td>B</td>
<td>B – Behind Shield @ 1m</td>
<td>4.50</td>
</tr>
<tr>
<td>C</td>
<td>C – Behind Gantry @ 4.35m</td>
<td>127</td>
</tr>
<tr>
<td>D</td>
<td>Foot of Couch</td>
<td>12.5</td>
</tr>
<tr>
<td>E</td>
<td>Far Side of CT Storage Room</td>
<td>19.0</td>
</tr>
<tr>
<td>F</td>
<td>Adjacent Operating Room</td>
<td>0.088</td>
</tr>
<tr>
<td>G</td>
<td>Sterile Area Entrance</td>
<td>22.0</td>
</tr>
<tr>
<td>H</td>
<td>Sterile Area Background</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Outside Corridor Door</td>
<td>0.024</td>
</tr>
<tr>
<td>J</td>
<td>Control Room</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.6: CT C/A/P Protocol Scatter Radiation Survey Results

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Exposure Rate (mR/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45° from Gantry @ 1m</td>
<td>320</td>
</tr>
<tr>
<td>B</td>
<td>Behind Shield @ 1m</td>
<td>57.0</td>
</tr>
<tr>
<td>C</td>
<td>Behind Gantry @ 4.35m</td>
<td>250</td>
</tr>
<tr>
<td>D</td>
<td>Foot of Couch</td>
<td>17.7</td>
</tr>
<tr>
<td>E</td>
<td>Sterile Area Entrance</td>
<td>5.80</td>
</tr>
<tr>
<td>F</td>
<td>90° from Gantry @ 2m</td>
<td>2.00</td>
</tr>
</tbody>
</table>

As shown by Location A in Table 3.5, which corresponds to a position just 1 meter from the center of the scanner and at a 45° angle, the exposure rate during i-Fluoro use can be as high as 800 mR/hr. This represents a common position held by a surgeon in the operating room while conducting fluoroscopy. Based upon this information, it is easy to determine that extended use of fluoroscopy can lead to a significant accumulation of exposure directly to a surgeon and, in particular, his or her hands if the surgeon is not careful or unable to move away from the table during intra-operative imaging.
3.2.2.1 Sources of Error

The accuracy of stated values is determined by the accuracy of chamber positioning (± 5 cm in each direction) and by the accuracy of the dosimeter (± 10% of reading between 10% and 100% of full-scale indication on any range, exclusive of energy response for Fluke 451P). Backscatter from the 10 cm air gap between floor and scanner gantry may cause additional variation in the radiation measurement for IMRIS VISIUS iCT.

3.2.3 Conclusion

The stray radiation air kerma was measured to be about 40-50% lower than the factory data. This may be explained as follows: as noted in Methods of Measurement, the exposure measurements were obtained with a Fluke Biomedical 451P, which has an internal ion chamber volume of 230 cc. When compared to the 500cc ion chamber used in the Siemens System Owner Manual, this is believed to account for the near half factor between the measured data and the company data. The increase in sensitivity from a larger volume ion chamber would present a higher level of metered radiation. The factory data is also listed as a maximum acceptable tolerance. Due to the unique gantry design of the IMRIS VISIUS iCT around the STRATON tube relative to the more traditional design of the Siemens SOMATOM Definition Flash, it is to be expected that it
would have a higher level of inherent filtration of stray radiation. We conclude that the stray radiations are comparable to the factory data.

### 3.3 Room Survey Utilizing RadEye G Personal Dose Meter

As noted previously, because each of these devices is intended to be used intra-operatively, one focus will be on the continuation of room survey data for common scan protocols. Radiation protection regulations require that all medical personal and staff not required to be present in the operating room during scanning leave. However, due to regulations such as those that require anesthesiologists to remain with anesthetized patients throughout their procedure, complete evacuation of the operating room is impractical.

Room surveys during scans were conducted with RadEye™ G (ThermoScientific, Inc., Erlangen, Germany) exposure rate meters. Designed for personal exposure rate recordings, the meters were placed in locations that would correspond to common locations for medical personal to stand during the use of each imaging device.
For the IMRIS VISIUS iCT, the location of each dosimeter within the room is labeled in Figure 3.6 with descriptions of each location as well as distance from the center of the scanner bore highlighted in Table 3.7. The layout represents the operating room as it would typically be set up for orthopedic surgery, with a focus on the locations for detectors being near equipment that could potentially be required to be monitored throughout an operation, a computer monitor positioned in the corner of the room for additional monitoring and operations, and the entrances to the operating room for momentary dose reconstruction purposes.
Table 3.7: IMRIS VISIUS iCT RadEye Location Details

<table>
<thead>
<tr>
<th>Position</th>
<th>RadEye S/N</th>
<th>Distance (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3332</td>
<td>4.08</td>
<td>Computer terminal in corner of OR</td>
</tr>
<tr>
<td>2</td>
<td>3387</td>
<td>2.08</td>
<td>Cart closest to sterile room entrance</td>
</tr>
<tr>
<td>3</td>
<td>3322</td>
<td>3.20</td>
<td>Cart furthest from couch</td>
</tr>
<tr>
<td>4</td>
<td>3331</td>
<td>2.29</td>
<td>Cart closest to OR entrance</td>
</tr>
<tr>
<td>5</td>
<td>3393</td>
<td>0.92</td>
<td>Behind portable shield</td>
</tr>
<tr>
<td>6</td>
<td>3300</td>
<td>N/A</td>
<td>Adjacent Sterile Room</td>
</tr>
<tr>
<td>7</td>
<td>3308</td>
<td>N/A</td>
<td>Hallway</td>
</tr>
</tbody>
</table>

Because the IMRIS VISIUS iCT was the only scanner tested capable of utilizing user adjustable protocols, three different exposure and dose rates are listed that correspond to the three protocols outlined in Chapter 1 for CT Head, CT i-Fluoro at 60 mAs/rotation, and CT Chest/Abdomen/Pelvis. These results are listed in Table 3.8. The
exposure and dose rates given correspond to the peak rates that occur during each of the scan protocols.

Table 3.8: IMRIS VISIUS iCT Room Survey Results

<table>
<thead>
<tr>
<th>Position</th>
<th>Exposure Rate (mR/hr)</th>
<th>Dose Rate (cGy/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CT Head</td>
<td>CT i-Fluoro</td>
</tr>
<tr>
<td>1</td>
<td>3.17</td>
<td>3.90</td>
</tr>
<tr>
<td>2</td>
<td>75.78</td>
<td>129.13</td>
</tr>
<tr>
<td>3</td>
<td>13.30</td>
<td>16.92</td>
</tr>
<tr>
<td>4</td>
<td>4.19</td>
<td>25.29</td>
</tr>
<tr>
<td>5</td>
<td>9.36</td>
<td>18.70</td>
</tr>
<tr>
<td>6</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>7</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

For the Mobius Airo mobile CT, Figure 3.7 shows the distribution of RadEye detectors whereas Table 3.9 corresponds to the description and distance of their placement. This operative suite setup represents a layout commonly used when implementing the mobile CT system do to the adjustments in table placement from the Mobius Airo’s built in patient table mount, but otherwise follows the same placement intention as for the VISIUS iCT. The results recorded from the RadEyes during Mobius Airo scanning are reported in Table 3.10 and also correspond to the average peak rates during each scan conducted with the mobile CT.
Figure 3.7: RadEye Locations for Mobius Airo

Table 3.9: Mobius Airo RadEye Location Details

<table>
<thead>
<tr>
<th>Position</th>
<th>RadEye S/N</th>
<th>Distance (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3308</td>
<td>4.57</td>
<td>OR cart closest to sterile room entrance</td>
</tr>
<tr>
<td>2</td>
<td>3322</td>
<td>2.64</td>
<td>OR cart closest to main room entrance</td>
</tr>
<tr>
<td>3</td>
<td>3331</td>
<td>5.46</td>
<td>Computer terminal in corner of OR</td>
</tr>
<tr>
<td>4</td>
<td>3332</td>
<td>0.76</td>
<td>Adjacent to patient couch</td>
</tr>
<tr>
<td>5</td>
<td>3386</td>
<td>2.29</td>
<td>Behind portable shield</td>
</tr>
</tbody>
</table>

Table 3.10: Mobius Airo Room Survey Results

<table>
<thead>
<tr>
<th>Position</th>
<th>Exposure Rate (mR/hr)</th>
<th>Dose Rate (cGy/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56.20</td>
<td>0.052</td>
</tr>
<tr>
<td>2</td>
<td>507.80</td>
<td>0.470</td>
</tr>
<tr>
<td>3</td>
<td>274.55</td>
<td>0.254</td>
</tr>
<tr>
<td>4</td>
<td>6471.54</td>
<td>5.99</td>
</tr>
<tr>
<td>5</td>
<td>1432.47</td>
<td>1.33</td>
</tr>
</tbody>
</table>
Finally, Figure 3.8 and Table 3.11 below outlines the corresponding positions of detectors placed for the Siemens ARCADIS Orbic 3D scanning, and the subsequent results are reported in Table 3.12. The same placement intentions were followed as before. The general placement of RadEyes for the Orbic 3D follows a hybrid between the VISIUS iCT and Airo as the device utilizes the room’s fixed table mounting location like the VISIUS iCT but allowed for closer positioning of clinicians or other medical personnel to the device due to a smaller overall footprint, like the Airo.

Figure 3.8: RadEye Locations for Siemens ARCADIS Orbic 3D
Table 3.11: Siemens ARCADIS Orbic 3D Location Details

<table>
<thead>
<tr>
<th>Position</th>
<th>RadEye S/N</th>
<th>Distance (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3332</td>
<td>4.08</td>
<td>Computer Terminal</td>
</tr>
<tr>
<td>2</td>
<td>3386</td>
<td>2.29</td>
<td>Scanner Operator</td>
</tr>
<tr>
<td>3</td>
<td>3322</td>
<td>0.89</td>
<td>Assistant Surgeon</td>
</tr>
<tr>
<td>4</td>
<td>3308</td>
<td>0.89</td>
<td>Assistant Surgeon</td>
</tr>
<tr>
<td>5</td>
<td>3331</td>
<td>2.08</td>
<td>Anesthesiologist</td>
</tr>
</tbody>
</table>

Table 3.12: Siemens ARCADIS Orbic 3D Room Survey Results

<table>
<thead>
<tr>
<th>Position</th>
<th>Exposure Rate (mR/hr)</th>
<th>Dose Rate (cGy/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>1.69E-05</td>
</tr>
<tr>
<td>2</td>
<td>3.19</td>
<td>2.91E-03</td>
</tr>
<tr>
<td>3</td>
<td>20.4</td>
<td>1.86E-02</td>
</tr>
<tr>
<td>4</td>
<td>26.6</td>
<td>2.42E-02</td>
</tr>
<tr>
<td>5</td>
<td>3.23</td>
<td>2.95E-03</td>
</tr>
</tbody>
</table>

3.3.1 Conclusion and Discussion

Despite the scanner being within factory acceptable standards for stray radiation, when we approach the device from a clinical perspective, we can see that in addition to the high entrance dose rate shown in Figure 2.6, Table 3.5 shows that medical personal in the operating room can also be at risk for high radiation exposure. Therefore, it is recommended that physicians using the IMRIS VISIUS iCT for CT i-Fluoro use be briefed on the potential for high exposure to patients and operators and that the following steps be taken to minimize the dose to all persons that may be present in the OR during scans: (1) evacuate all medical personnel from the OR that are not essential during scanning; (2) ensure all medical personnel that remain in the room are wearing
full personal protective equipment (PPE) including apron, thyroid shield, and glasses; and (3) ensure remaining medical personnel utilize available portable lead shielding.

As we would expect from the initial beam data as well as the geometry and design of the C-Arm system compared to the traditional CT, the dose rates from the Siemens ARCADIS Orbic 3D are significantly lower than both of the CT scanners. However, most significant is the high dose rates that occur when operating the Mobius Airo mobile CT, in some cases as potentially as high as nearly 6.5 R/hr when within a 1 meter radius from the device. Because the scanner tube is operating at similar parameters when compared to the IMRIS device, but the Mobius mobile system has significantly less inherent shielding in its design, it is to be expected that the dose rate from leakage would be higher than the ceiling gantry mounted IMRIS. The scatter radiation combined with the leakage from the Mobius gives rise to significant dose rate concerns, even more so than originally developed for the VISIUS iCT. Because the scanner is a mobile system, the Airo requires an in-room operator unlike the VISIUS iCT which is operated from the console within the shielded control room. While the device was tested by Duke’s Clinical Imaging Physics Group for compliance and passed, the safety considerations for the Mobius Airo should be considered [18]. However, because the Mobius Airo lacks the fluoroscopic capability of the IMRIS VISIUS iCT, practical scan time maximums are significantly lower. Despite this, previous recommendations
for safety regarding the IMRIS VISIUS iCT should be applied to and reinforced for use of the Mobius Airo, with the addition of ensuring that proper rotation of scanner operators occurs in order to practice ALARA throughout the department.
4. Intra-operative Imaging Devices Comparison

4.1 Introduction

The Orthopedic Surgery Division in the Duke Medicine Pavilion (DMP) performs numerous procedures per week. One of the most common operations is the posterior lumbar fusion of three to five lumbar vertebral bodies. Often, this is a response to ruptured, compressed, or otherwise damaged intervertebral discs. Fusing the vertebra together with metal hardware reinforces the spine and takes pressure off the compromised discs. The standard operating procedure for this surgery starts with accurate pre-operative imaging for planning purposes. Intra-operative imaging of the lumbar spine, or so-called “image guided surgery” through the use of different computer assisted surgery (CAS) devices, continues throughout the operation for placement verification. Following completion of surgical hardware installation, immediate post-operative imaging occurs in order to confirm successful placement.

Orthopedic surgeons at Duke utilize one such CAS device, a BrainLAB system that takes standardized Digital Imaging and Communications in Medicine (DICOM) output files from any number of diagnostic imaging devices. Prior to imaging a patient, specific markers that are reflective both in the visible light and x-ray spectra are placed on the patient’s skin. These markers are used as reference points for the Brain Lab system to conduct semi-automated image guided orthopedic surgery. Because the Brain
Lab system can utilize the standardized DICOM image output format, surgeons have a wide selection of devices at their command to utilize for intra-operative imaging. The DMP is host to four different imaging devices from as many different manufacturers. We have already discussed and gathered preliminary data on the IMRIS VISIS iCT. A second CT based imaging system is available, a Mobius Airo mobile CT system, as well as two different C-arm based scanners, a Siemens ARCADIS Orbic 3D and a GE OEC 9900 Elite. The scope of this project is to begin gathering data on the characteristics of these various devices while completing full analysis of the IMRIS VISIUS iCT.

While a similar approach has been applied to organ dosimetry in urology cases, there is no current data on such organ dosimetry for orthopedic spine use [19] [20]. Despite the discoveries highlighted in other clinical dosimetry cases, there is novelty in the exploration of organ dosimetry in this region and effective dose comparison across scanners that are not used for diagnostic purposes. Therefore, we will also briefly analyze the relationship between dose and image quality for the machines. It is important to note that the image quality standard for surgical uses are lower than what is generally accepted for diagnostic scans. In fact, in the case of the Mobius Airo, it would fail American College of Radiology (ACR) accreditation for diagnostic scanning for artifacts and high contrast resolution [18].
Of particular interest to collaborating physicians is the significance of patient body mass in relation to absorbed dose. Due to the nature of orthopedic surgery of the lumbar spine, a significant number of patients that receive surgery are overweight or obese. Of the machines tested, the IMRIS VISIUS iCT is the only one capable of switching between fixed or automated tube potential and tube current modulation through Siemens’s proprietary “CarekVp” and “CareDose4D”. The remaining devices, the Mobius Airo and the Siemens ARCADIS Orbic 3D, have minimal operator adjustable inputs and instead rely upon built in software to modulate tube potential and tube current for optimal image quality.
The organ dose from imaging devices to organs within the lumbar region will be measured and compared between machines, as well as to themselves relative to increasing patient body mass. Image quality changes with increase in patient size will also be compared.

**4.2 Beam Data**

Beam data regarding tube potential and half value layers for the IMRIS VIUIS iCT that were determined through the methods described in Chapter 1 from RTI Piranha 557 S/N: CB2-08080027; calibrated: 06/27/2014 and are summarized in Table 4.1.
Table 4.1: IMRIS VISIUS iCT Beam Data

<table>
<thead>
<tr>
<th>Operational Tube Potential</th>
<th>118.4 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVL</td>
<td>7.66 mm Al</td>
</tr>
<tr>
<td>Effective Energy</td>
<td>53.64 keV</td>
</tr>
<tr>
<td>f-factor (soft tissue)</td>
<td>0.934 cGy/R</td>
</tr>
</tbody>
</table>

Beam data for the Mobius Airo was collected in an identical manner as the VISIUS iCT utilizing the same Piranha 557 and is summarized in Table 4.2.

Table 4.2: Mobius Airo Beam Data

<table>
<thead>
<tr>
<th>Operational Tube Potential</th>
<th>122.3 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVL</td>
<td>7.21 mm Al</td>
</tr>
<tr>
<td>Effective Energy</td>
<td>51.31 keV</td>
</tr>
<tr>
<td>f-factor (soft tissue)</td>
<td>0.925 cGy/R</td>
</tr>
</tbody>
</table>

Because the Siemens ARACADIS Orbic 3D produces such low exposure rates, we were unable to use the Piranha 557 meter to measure the HVL of the device. Instead, a 10x5-0.18 ion chamber connected to a RadCal 9015 electrometer was placed in the beam field. An initial thickness of aluminum was utilized in the beam field to create the equivalent build-up of our CRICS Model 701-D adult male anthropomorphic phantom necessary to force the scanner’s automatic tube potential modulation to 83 kVp. A single shot exposure was produced from the machine and the ion chamber reading was recorded. Additional layers of aluminum were progressively added to the beam field and exposure readings from the ion chamber were recorded for each thickness. Figure
4.3 and Table 4.3 display the results for HVL determination and soft tissue f-factor calculation utilizing the effective energy to determine mass attenuation values and application of Equation 2.1.

![Figure 4.3: HVL Determination of Siemens ARCADIS Orbic 3D](image)

**Table 4.3: Siemens ARCADIS Orbic 3D Beam Data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Tube Potential</td>
<td>83 kVp</td>
</tr>
<tr>
<td>HVL</td>
<td>7.12 mm Al</td>
</tr>
<tr>
<td>Effective Energy</td>
<td>32.76 keV</td>
</tr>
<tr>
<td>Added Filtration for Calibration</td>
<td>11.24 cm Al</td>
</tr>
<tr>
<td>f-factor (soft tissue)</td>
<td>0.914 cGy/R</td>
</tr>
</tbody>
</table>

Beam data for the GE OEC was collected in an identical manner as the VISIUS iCT utilizing the same Piranha 557 and is summarized in Table 4.4.
Table 4.4: GE OEC 9900 Elite Beam Data

<table>
<thead>
<tr>
<th>Operational Tube Potential</th>
<th>75 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVL</td>
<td>4.25 mm Al</td>
</tr>
<tr>
<td>Effective Energy</td>
<td>46.6 keV</td>
</tr>
<tr>
<td>f-factor (soft tissue)</td>
<td>0.920 cGy/R</td>
</tr>
</tbody>
</table>

Additional SpekCalc beam spectra data for each scanner can be found in Appendix A. Comparing values from Table 4.1 and Table 4.2 show that the two CT based systems are more similar to each other than the C-Arm based system, which is to be expected. Despite not being able to manually adjust tube potential, the automatic modulation on the Airo maintains a similar tube potential to the VISIUS iCT, near 120 kVp, which is significantly higher than the ARCADIS Orbic 3D’s 83 kVp and the GE OEC 9900 Elite’s 75 kVp. Therefore, the two CT scanners will generally be compared against each other while the two C-Arms are compared to each other in a similar manner.

4.3 Materials and Methods

Organ dosimetry was conducted through the use of calibrated Model TN-RD-60 MOSFET AutoSense™ Patient Dose Verification System (Best Medical, Canada). 20 high sensitivity Model TN-1002RD dosimeters are connected to four different Model TN-RD-15 readers through a Model TN-RD-22 bias supply. AutoSense™ PC Software, TN-RD-45, allows reading and data exportation through any Microsoft Windows PC via USB.
An example of the equipment utilized is displayed in Figure 4.4. Prior to utilizing the MOSFET system, calibration was conducted to develop a calibration factor to convert from the MOSFET readings of mV to absorbed dose in mGy as detailed in Chapter 1. Each MOSFET dosimeter has an individual calibration factor, and sets of calibration factors are developed for each diagnostic imaging device tested.

Figure 4.4: TN-RD-60 MOSFET AutoSense™ Patient Dose Verification System

A CIRS Model 701-D adult male anthropomorphic phantom was used throughout the experiment. Under normal conditions, the phantom represents an adult male of weight 160 lbs and corresponding Body Mass Index (BMI) of 23.0 [21]. Two layers of 4 cm thick adipose equivalent material were progressively added to the abdominal region in order to increase the phantom’s equivalent mass to 179 lbs and 198 lbs, which correspond to overweight and obese BMI values of 27.2 and 30.1, respectively. The locations used for organ dosimetry within the phantom and
corresponding dosimeter position and slice location are listed in Table 4.5. Organ locations were chosen based off of radiosensitive organs in the abdominal area from two phantom slices superior to inferior of the scan range [3].

Model 10X5-0.18 ion chambers both connected to Model 9015 electrometers were placed in the center of the FOV along the skin of the phantom to record dose.

Table 4.5: MOSFET Dosimeter Organ Location List

<table>
<thead>
<tr>
<th>Organ</th>
<th>Phantom Slice</th>
<th>Dosimeter Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>22</td>
<td>154</td>
</tr>
<tr>
<td>Spleen</td>
<td>22</td>
<td>157</td>
</tr>
<tr>
<td>Active Bone Marrow (T Spine)</td>
<td>22</td>
<td>163</td>
</tr>
<tr>
<td>Pancreas</td>
<td>23</td>
<td>169</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>23</td>
<td>173</td>
</tr>
<tr>
<td>Gall Bladder</td>
<td>24</td>
<td>181</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>25</td>
<td>197</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>25</td>
<td>198</td>
</tr>
<tr>
<td>Active Bone Marrow (L Spine)</td>
<td>25</td>
<td>200</td>
</tr>
<tr>
<td>Stomach</td>
<td>26</td>
<td>201</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>26</td>
<td>206</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>27</td>
<td>210</td>
</tr>
<tr>
<td>Active Bone Marrow (L Spine)</td>
<td>27</td>
<td>211</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>27</td>
<td>212</td>
</tr>
<tr>
<td>Colon</td>
<td>29</td>
<td>216</td>
</tr>
<tr>
<td>Colon</td>
<td>29</td>
<td>217</td>
</tr>
<tr>
<td>Active Bone Marrow (L Spine)</td>
<td>29</td>
<td>218</td>
</tr>
<tr>
<td>Active Bone Marrow (Pelvis)</td>
<td>30</td>
<td>220</td>
</tr>
<tr>
<td>Active Bone Marrow (Pelvis)</td>
<td>30</td>
<td>221</td>
</tr>
<tr>
<td>Active Bone Marrow (Sacrum)</td>
<td>31</td>
<td>232</td>
</tr>
</tbody>
</table>
An example of MOSFET placement within the phantom is displayed in Figure 4.5. In all cases, the MOSFET cables were routed out the phantoms anterior side in order to reduce the interference on the emitter side of the C-Arm when the phantom is placed prone on the couch, as a patient would be for spinal surgery. In cases of data collection for the C-Arm, MOSFET detector faces were placed ensuring that the face of the detector was on the emitter side of the device, as well.

Figure 4.5: Model 701-D Phantom with MOSFET Dosimeters
4.3.1 Effective Dose Calculation

Because each MOSFET dosimeter is measuring a specific point dose, calculating effective dose directly from these point doses and appropriate ICRP 103 tissue weighting factors can be misleading. Utilizing this method can lead to effective dose calculations that are on the order of 50 – 70% higher that validated simulation determined effective doses [22]. In order to accurately calculate effective dose from point dose determinations, a partial volume correction factor (PVCF) is applied to each point dose. For skin dose, the “rule of nines” is applied, which is a method originally developed for estimating the surface area of skin affected for burn victims and validated for skin dosimetry use. For bone marrow, the validated PVCF is based off of mass percentage relative to total body bone marrow [23]. For remaining organs, the PVCF is based off of the percent of organ volume present in the scan’s FOV. Therefore, the applied equation for effective dose is given below:

\[ ED \ (mSv) = \sum PVCF_T \times W_T \times PD_T \]  \hspace{1cm} (4.1)

where PVCF \(_T\) is the partial volume correction factor for the appropriate tissue, \( W_T \) is the tissue weighting factor from ICRP 103, and PD\(_T\) is the experimentally determined point dose for each organ.
4.4 Results and Discussion

When conducting intra-operative scans with the IMRIS VISIUS iCT, the full length of the lumbar spine is imaged regardless of whether the first three or all five vertebrae are to be fused. However, for potential comparison to the C-Arm system, scans were also conducted for a field of views centered on the L2 and L4 vertebrae and extended to the adjacent vertebral bodies. The specific protocols used when imaging the normal, overweight, and obese equivalent anthropomorphic phantom are detailed in Table 4.6.

Table 4.6: IMRIS VISIUS iCT Scan Parameters

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Overweight</th>
<th>Obese</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Potential (kVp)</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Effective mAs</td>
<td>150</td>
<td>308</td>
<td>632</td>
</tr>
<tr>
<td>CTDI&lt;sub&gt;vol&lt;/sub&gt; (mGy)</td>
<td>11.45</td>
<td>23.59</td>
<td>48.28</td>
</tr>
<tr>
<td>DLP (mGy·cm)</td>
<td>263.2</td>
<td>542.0</td>
<td>1109.4</td>
</tr>
<tr>
<td>Care Dose 4D</td>
<td>on</td>
<td>on</td>
<td>on</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Rotation</td>
<td>Axial</td>
<td>Axial</td>
<td>Axial</td>
</tr>
</tbody>
</table>

The organ dosimetry results for the IMRIS VISIUS iCT are listed in Table 4.7 and graphically displayed in Figure 4.6. Due to the high exposure rate of traditional CT scanner, only one CT scan was necessary to accumulated significant voltage across each MOSFET, and the results display the corresponding dose per scan averaged through
three different data collection cycles with the corresponding standard deviation also listed.

Table 4.7: IMRIS VISIUS iCT Organ Dose Results

<table>
<thead>
<tr>
<th>Description</th>
<th>Normal Avg</th>
<th>Normal SD</th>
<th>Overweight Avg</th>
<th>Overweight SD</th>
<th>Obese Avg</th>
<th>Obese SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>45.32</td>
<td>1.34</td>
<td>38.14</td>
<td>1.13</td>
<td>39.27</td>
<td>2.71</td>
</tr>
<tr>
<td>Spleen</td>
<td>48.37</td>
<td>2.16</td>
<td>48.66</td>
<td>4.52</td>
<td>50.33</td>
<td>1.78</td>
</tr>
<tr>
<td>BM, Thoracic</td>
<td>20.01</td>
<td>1.65</td>
<td>12.50</td>
<td>6.00</td>
<td>15.38</td>
<td>8.69</td>
</tr>
<tr>
<td>Pancreas</td>
<td>48.03</td>
<td>2.29</td>
<td>62.76</td>
<td>10.86</td>
<td>53.95</td>
<td>7.12</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>53.68</td>
<td>2.61</td>
<td>68.42</td>
<td>1.75</td>
<td>80.15</td>
<td>2.84</td>
</tr>
<tr>
<td>Gall Bladder</td>
<td>36.37</td>
<td>2.00</td>
<td>49.65</td>
<td>6.75</td>
<td>65.67</td>
<td>4.12</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>55.89</td>
<td>9.20</td>
<td>81.20</td>
<td>13.11</td>
<td>101.24</td>
<td>15.94</td>
</tr>
<tr>
<td>BM, Lumbar</td>
<td>27.67</td>
<td>7.43</td>
<td>31.93</td>
<td>8.71</td>
<td>49.88</td>
<td>16.76</td>
</tr>
<tr>
<td>Stomach</td>
<td>34.93</td>
<td>0.82</td>
<td>55.67</td>
<td>2.16</td>
<td>91.72</td>
<td>2.01</td>
</tr>
<tr>
<td>Colon</td>
<td>48.43</td>
<td>1.96</td>
<td>62.52</td>
<td>5.31</td>
<td>90.36</td>
<td>3.25</td>
</tr>
<tr>
<td>BM, Pelvis</td>
<td>27.80</td>
<td>5.23</td>
<td>48.30</td>
<td>14.46</td>
<td>80.84</td>
<td>8.09</td>
</tr>
<tr>
<td>BM, Sacrum</td>
<td>20.63</td>
<td>1.69</td>
<td>42.83</td>
<td>5.08</td>
<td>79.85</td>
<td>3.23</td>
</tr>
<tr>
<td>Skin</td>
<td>32.13</td>
<td>1.71</td>
<td>26.32</td>
<td>1.67</td>
<td>49.74</td>
<td>0.75</td>
</tr>
</tbody>
</table>
The above results follow trends that one would inspect. For each BMI category of our phantom, the doses to organs within the central FOV receive a higher dose than those that are on the edge or outside the FOV due to internal scatter radiation. Also, as scan protocol parameters of CTDIvol and DLP increased with increasing patient weight, so did the corresponding individual organ doses. The exceptions to this general observation (liver, spleen, pancreas, and thoracic spine) are attributed to the fact that the additional layers of adipose equivalent material do not extend beyond the FOV, as shown by Figure 4.7. Of specific interest is the bone marrow within the lumbar spine itself, which received $27.67 \pm 7.43$ mGy, $31.93 \pm 8.71$ mGy, and $49.88 \pm 16.76$ mGy per scan for increasing BMI values. The organ with the highest individual absorbed dose
was the right kidney, which received 55.89 ± 9.20 mGy, 81.20 ± 13.11 mGy, and 101.24 ± 15.94 mGy.

**Figure 4.7: Single Layer Adipose Equivalent Material Added to Model 701-D**

The data collection process for the Mobius Airo was nearly identical to that of the IMRIS VISIUS iCT. The most significant deviation is rather than implementing the established clinical protocols in place, the complete and independent modulation of all parameters are handled by the on-board proprietary software with the Airo, which fixes the tube potential to 120 kVp for all scans and the CTDI\text{vol} for patient weight. It accomplishes this through real time tube current modulation based on the following equation [18]:

\[
1.37 \left( \frac{mAs}{kg} \right) \times \text{patient weight (kg)} = \text{prescribed mAs}
\]  

(4.2)
varying the effective mAs to 110 mAs, 127.59 mAs, and 141 mAs for normal, overweight, and obese phantoms, respectively. Organ dose per scan results for the three testing cycles that occurred on the Airo are listed in Table 4.8 and graphically displayed in Figure 4.8 similar to results for the VISIUS iCT above.

Table 4.8: Mobius Airo Organ Dose Results

<table>
<thead>
<tr>
<th>Description</th>
<th>Normal Avg</th>
<th>Normal SD</th>
<th>Overweight Avg</th>
<th>Overweight SD</th>
<th>Obese Avg</th>
<th>Obese SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>19.86</td>
<td>1.12</td>
<td>13.61</td>
<td>2.20</td>
<td>12.61</td>
<td>1.20</td>
</tr>
<tr>
<td>Spleen</td>
<td>24.69</td>
<td>1.10</td>
<td>18.16</td>
<td>1.40</td>
<td>14.52</td>
<td>1.26</td>
</tr>
<tr>
<td>BM, Thoracic</td>
<td>10.37</td>
<td>0.80</td>
<td>8.51</td>
<td>0.46</td>
<td>5.98</td>
<td>2.39</td>
</tr>
<tr>
<td>Pancreas</td>
<td>13.35</td>
<td>14.85</td>
<td>12.49</td>
<td>4.97</td>
<td>16.72</td>
<td>0.26</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>23.35</td>
<td>0.82</td>
<td>18.10</td>
<td>1.87</td>
<td>13.32</td>
<td>1.04</td>
</tr>
<tr>
<td>Gall Bladder</td>
<td>22.47</td>
<td>2.70</td>
<td>14.84</td>
<td>3.07</td>
<td>7.78</td>
<td>0.43</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>23.94</td>
<td>0.83</td>
<td>19.38</td>
<td>0.69</td>
<td>14.82</td>
<td>0.77</td>
</tr>
<tr>
<td>BM, Lumbar</td>
<td>10.49</td>
<td>1.01</td>
<td>8.31</td>
<td>1.20</td>
<td>5.15</td>
<td>1.34</td>
</tr>
<tr>
<td>Stomach</td>
<td>26.66</td>
<td>0.52</td>
<td>23.36</td>
<td>0.00</td>
<td>17.37</td>
<td>1.04</td>
</tr>
<tr>
<td>Colon</td>
<td>20.31</td>
<td>1.65</td>
<td>17.59</td>
<td>0.70</td>
<td>10.42</td>
<td>1.53</td>
</tr>
<tr>
<td>BM, Pelvis</td>
<td>16.74</td>
<td>2.72</td>
<td>13.61</td>
<td>2.56</td>
<td>8.33</td>
<td>2.56</td>
</tr>
<tr>
<td>BM, Sacrum</td>
<td>3.51</td>
<td>1.17</td>
<td>4.24</td>
<td>0.84</td>
<td>3.27</td>
<td>0.51</td>
</tr>
<tr>
<td>Skin</td>
<td>37.15</td>
<td>0.21</td>
<td>34.73</td>
<td>0.34</td>
<td>41.69</td>
<td>1.14</td>
</tr>
</tbody>
</table>
The pancreas did not behave in the same manner as the rest of the internal organs, but the high statistical deviation for both normal and overweight phantoms points toward a variation in the MOSFET detector at that specific position. Similar to the superior organs not being covered by the complete layer of simulated adipose, it is likely that the absorbed dose measured in the sacrum’s bone marrow was too inferior and also mostly scatter, which would account for the slight deviation in expected dose reduction behavior.

For the bone marrow within the lumbar spine, it received $10.45 \pm 1.01$ mGy, $8.31 \pm 1.20$ mGy, and $5.15 \pm 1.34$ mGy per scan for increasing BMI values. The organ with the highest individual absorbed dose on average was the stomach, which received $26.66 \pm 0.52$ mGy, $23.36 \pm 0.00$ mGy, and $17.37 \pm 1.04$ mGy.
The Siemens ARCADIS Orbic 3D deviates significantly from the previously mentioned CT scanners. A unique feature for this C-Arm is that its rotation is isocentric. It takes a nominal 60 seconds for the Orbic 3D to completely rotate through its 190° arc, and it takes a single planar image every third degree in order to form its tomogram. The Orbic 3D has a narrower field of view when compared to conventional CT machines. Because of this, the only a portion of the lumbar spine can be imaged at one time. When utilized for a two level fusion operation that fuse the L1 through L3 vertebral bodies, the field of view is centered upon the L2 vertebrae. For full four level lumbar fusions that join the L1 through L5 bodies, a second set of scans is taken centered on the L4 vertebrae. An example of the field of view from an anthropomorphic phantom is displayed in Figure 4.9. These differences required modified methods for collecting the organ dosimetry compared to the previous two scanners. Similar to the Airo, the Orbic 3D uses built in proprietary automatic modulation to adjust tube parameters. Throughout testing, the device maintained a nominal 83 kVp tube potential and modulated tube current from 8–11 mA for each independent slice.
Figure 4.9: Siemens ARCADIS Orbic 3D FOV

Because of this inability to image the full lumbar spine, no L1 through L5 data could be collected for this device. The organ doses are instead broken down into two scans for the superior and inferior regions. Also, similar to the low exposure values affecting the ability to utilize a Piranha 557, the exposure rate of this imaging device is so low relative to a CT scanner, it was necessary to complete 10 complete scans per cycle in order to accumulate enough voltage across each MOSFET. Each 10 scan cycle was completed three times for both superior and inferior positions for all three BMI equivalent phantom setups. The displayed data represents the average dose per each
individual scan conducted with the C-Arm in Table 4.9, Table 4.10, and Table 4.11. The results are graphically displayed in Figure 4.10 and Figure 4.11.

Table 4.9: Siemens ARCADIS Orbic 3D Organ Dose Results - Normal

<table>
<thead>
<tr>
<th>Description</th>
<th>L1-L3 Position Average</th>
<th>L1-L3 Position Std Dev</th>
<th>L3-L5 Position Average</th>
<th>L3-L5 Position Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>0.16</td>
<td>0.05</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Spleen</td>
<td>0.62</td>
<td>0.05</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>BM, Thoracic</td>
<td>0.09</td>
<td>0.15</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Pancreas</td>
<td>0.59</td>
<td>0.09</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>0.50</td>
<td>0.04</td>
<td>0.38</td>
<td>0.03</td>
</tr>
<tr>
<td>Gall Bladder</td>
<td>1.12</td>
<td>0.08</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>0.65</td>
<td>0.08</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>BM, Lumbar</td>
<td>0.20</td>
<td>0.05</td>
<td>0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>Stomach</td>
<td>1.22</td>
<td>0.23</td>
<td>0.41</td>
<td>0.04</td>
</tr>
<tr>
<td>Colon</td>
<td>0.05</td>
<td>0.07</td>
<td>1.25</td>
<td>0.10</td>
</tr>
<tr>
<td>BM, Pelvis</td>
<td>0.00</td>
<td>0.00</td>
<td>0.32</td>
<td>0.12</td>
</tr>
<tr>
<td>BM, Sacrum</td>
<td>0.00</td>
<td>0.00</td>
<td>0.30</td>
<td>0.06</td>
</tr>
<tr>
<td>Skin Entrance</td>
<td>0.96</td>
<td>0.19</td>
<td>1.94</td>
<td>0.41</td>
</tr>
<tr>
<td>Skin Exit</td>
<td>0.16</td>
<td>0.19</td>
<td>0.12</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Table 4.10: Siemens ARCADIS Orbic 3D Organ Dose Results - Overweight

<table>
<thead>
<tr>
<th>Description</th>
<th>L1-L3 Position</th>
<th>L3-L5 Position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Std Dev</td>
</tr>
<tr>
<td>Liver</td>
<td>0.35</td>
<td>0.07</td>
</tr>
<tr>
<td>Spleen</td>
<td>1.02</td>
<td>0.13</td>
</tr>
<tr>
<td>BM, Thoracic</td>
<td>0.18</td>
<td>0.10</td>
</tr>
<tr>
<td>Pancreas</td>
<td>1.15</td>
<td>0.06</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>0.73</td>
<td>0.08</td>
</tr>
<tr>
<td>Gall Bladder</td>
<td>1.25</td>
<td>0.09</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>0.73</td>
<td>1.00</td>
</tr>
<tr>
<td>BM, Lumbar</td>
<td>0.32</td>
<td>0.06</td>
</tr>
<tr>
<td>Stomach</td>
<td>1.64</td>
<td>0.11</td>
</tr>
<tr>
<td>Colon</td>
<td>0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>BM, Pelvis</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>BM, Sacrum</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Skin Entrance</td>
<td>1.92</td>
<td>0.05</td>
</tr>
<tr>
<td>Skin Exit</td>
<td>0.17</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Table 4.11: Siemens ARCADIS Orbic 3D Organ Dose Results - Obese

<table>
<thead>
<tr>
<th>Description</th>
<th>L1-L3 Position</th>
<th></th>
<th>L3-L5 Position</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Std Dev</td>
<td>Average</td>
<td>Std Dev</td>
</tr>
<tr>
<td>Liver</td>
<td>0.30</td>
<td>0.05</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td>Spleen</td>
<td>0.83</td>
<td>0.07</td>
<td>0.20</td>
<td>0.07</td>
</tr>
<tr>
<td>BM, Thoracic</td>
<td>0.13</td>
<td>0.20</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Pancreas</td>
<td>0.84</td>
<td>0.08</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>0.57</td>
<td>0.11</td>
<td>0.48</td>
<td>0.06</td>
</tr>
<tr>
<td>Gall Bladder</td>
<td>0.90</td>
<td>0.12</td>
<td>0.27</td>
<td>0.05</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>0.39</td>
<td>0.10</td>
<td>0.47</td>
<td>0.12</td>
</tr>
<tr>
<td>BM, Lumbar</td>
<td>0.19</td>
<td>0.07</td>
<td>0.20</td>
<td>0.03</td>
</tr>
<tr>
<td>Stomach</td>
<td>1.29</td>
<td>0.24</td>
<td>1.31</td>
<td>0.08</td>
</tr>
<tr>
<td>Colon</td>
<td>0.08</td>
<td>0.07</td>
<td>0.43</td>
<td>0.10</td>
</tr>
<tr>
<td>BM, Pelvis</td>
<td>0.04</td>
<td>0.07</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>BM, Sacrum</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>Skin Entrance</td>
<td>3.19</td>
<td>0.09</td>
<td>3.01</td>
<td>0.08</td>
</tr>
<tr>
<td>Skin Exit</td>
<td>0.05</td>
<td>0.01</td>
<td>0.10</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Figure 4.10: Siemens ARCADIS Orbic 3D Organ Dose per Scan – L1-L3
The shift in dose concentration from superior to inferior with corresponding shift in the vertebral body in the center of the FOV of the scanner is well behaved. The lumbar spine received a dose of $0.20 \pm 0.05 \text{ mGy}$, $0.32 \pm 0.07 \text{ mGy}$, and $0.19 \pm 0.07 \text{ mGy}$ for increasing BMI and $0.14 \pm 0.05 \text{ mGy}$, $0.38 \pm 0.09 \text{ mGy}$, and $0.20 \pm 0.03 \text{ mGy}$ for increasing BMI for both superior and inferior scans, respectively.

The GE OEC 9900 Elite is similar to the Siemens ARCADIS Orbic 3D in its C Arm construction. However, it operates like a traditional fluoroscopic device, requiring manual alignment and offering no rotation nor corresponding reconstruction. Like the Siemens ARCADIS Orbic 3D, the GE OEC 9900 Elite offers very low exposure rate. However, unlike its counterpart, it does not have the endurance to continue scanning.
long enough to achieve significant threshold shift on the MOSFET dosimeters before being plagued by long tube cool time.

In order to determine the specific organ doses and effective dose for this device, PCXMC software was used along with the current-time product from typical anterior-posterior (AP) and left lateral (LLAT) scans performed when using the GE OEC 9900. This information, along with the beam data and manufacturer’s technical specifications were utilized to combine both angle scans in the simulation data for overall superior and inferior scans in a similar manner as the experimental scans conducted on the Siemens ARACDIS Orbic 3D [24]. The resultant data is displayed in Table 4.12 below and graphically represented by Figure 4.12 and Figure 4.13.

Table 4.12: GE OEC 9900 Elite PCXMC Organ Dose Results

<table>
<thead>
<tr>
<th>Dose per scan (mGy)</th>
<th>Normal L1-L3</th>
<th>Normal L3-L5</th>
<th>Overweight L1-L3</th>
<th>Overweight L3-L5</th>
<th>Obese L1-L3</th>
<th>Obese L3-L5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>0.28</td>
<td>0.12</td>
<td>0.56</td>
<td>0.22</td>
<td>1.07</td>
<td>0.28</td>
</tr>
<tr>
<td>Spleen</td>
<td>1.32</td>
<td>0.29</td>
<td>0.82</td>
<td>0.75</td>
<td>2.18</td>
<td>0.85</td>
</tr>
<tr>
<td>BM, Thoracic</td>
<td>0.14</td>
<td>0.04</td>
<td>0.19</td>
<td>0.10</td>
<td>0.37</td>
<td>0.12</td>
</tr>
<tr>
<td>Pancreas</td>
<td>0.79</td>
<td>0.19</td>
<td>0.90</td>
<td>0.45</td>
<td>1.98</td>
<td>0.56</td>
</tr>
<tr>
<td>Kidney (Left)</td>
<td>0.44</td>
<td>0.22</td>
<td>0.57</td>
<td>0.50</td>
<td>0.85</td>
<td>0.57</td>
</tr>
<tr>
<td>Gall Bladder</td>
<td>0.78</td>
<td>0.66</td>
<td>1.71</td>
<td>1.25</td>
<td>3.22</td>
<td>1.65</td>
</tr>
<tr>
<td>Kidney (Right)</td>
<td>0.44</td>
<td>0.22</td>
<td>0.57</td>
<td>0.50</td>
<td>0.85</td>
<td>0.57</td>
</tr>
<tr>
<td>BM, Lumbar</td>
<td>0.64</td>
<td>0.46</td>
<td>1.04</td>
<td>0.95</td>
<td>1.53</td>
<td>1.04</td>
</tr>
<tr>
<td>Stomach</td>
<td>1.24</td>
<td>0.53</td>
<td>1.57</td>
<td>1.13</td>
<td>2.86</td>
<td>1.34</td>
</tr>
<tr>
<td>Colon</td>
<td>0.37</td>
<td>0.43</td>
<td>0.82</td>
<td>0.89</td>
<td>1.11</td>
<td>1.05</td>
</tr>
<tr>
<td>BM, Pelvis</td>
<td>0.18</td>
<td>0.33</td>
<td>0.68</td>
<td>0.77</td>
<td>0.42</td>
<td>0.83</td>
</tr>
<tr>
<td>BM, Sacrum</td>
<td>0.09</td>
<td>0.06</td>
<td>0.17</td>
<td>0.15</td>
<td>0.22</td>
<td>0.17</td>
</tr>
<tr>
<td>Skin</td>
<td>0.12</td>
<td>0.08</td>
<td>0.16</td>
<td>0.15</td>
<td>0.23</td>
<td>0.16</td>
</tr>
</tbody>
</table>
One of the most notable features of the organ dose data is the lack of standard deviation for each of the corresponding values. Because PCXMC is a MC based simulation software, there is no way to determine the systematic error from the scanner.
and the dosimeter results. However, the values are in the expected range given the scan parameters. The lumbar spine received a dose of 0.64 mGy, 1.04 mGy, and 1.53 mGy for increasing BMI and 0.46 mGy, 0.95 mGy, and 1.04 mGy for increasing BMI for both superior and inferior scans, respectively.

In order to establish a more uniform basis for comparison, the effective dose per scan of scan device was calculated. For radiation protection briefing and summary purposes, each effective dose was also related to an equivalent number of plane chest radiographs as well as years or days of equivalent natural background radiation in the United States of America based off of current NCRP estimates [25].

For the IMRIS VISIUS iCT, Table 4.13 below displays these values.

Table 4.13: Effective Dose – IMRIS VISIUS iCT

<table>
<thead>
<tr>
<th></th>
<th>ED (mSv)</th>
<th># Chest X-ray</th>
<th>Eq Bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>12.00 ± 0.30</td>
<td>120.0</td>
<td>3.9 years</td>
</tr>
<tr>
<td>Overweight</td>
<td>15.91 ± 0.75</td>
<td>159.2</td>
<td>5.1 years</td>
</tr>
<tr>
<td>Obese</td>
<td>23.23 ± 0.55</td>
<td>232.3</td>
<td>7.5 years</td>
</tr>
</tbody>
</table>

These values correspond to a 32.6% and 93.6% increase in effective dose for a corresponding 18.2% and 30.9% increase for overweight and obese BMI values, respectively, relative to a normal BMI.

Table 4.14 below reflects the corresponding information for the Mobius Airo.
Table 4.14: Effective Dose – Mobius Airo

<table>
<thead>
<tr>
<th></th>
<th>ED (mSv)</th>
<th># Chest X-ray</th>
<th>Eq Bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>5.90 ± 0.25</td>
<td>59.0</td>
<td>1.9 years</td>
</tr>
<tr>
<td>Overweight</td>
<td>4.97 ± 0.12</td>
<td>49.7</td>
<td>1.6 years</td>
</tr>
<tr>
<td>Obese</td>
<td>3.44 ± 0.21</td>
<td>34.4</td>
<td>1.1 years</td>
</tr>
</tbody>
</table>

These values correspond to a 15.7% and 41.7% decrease in effective dose for a corresponding 18.2% and 30.9% increase for overweight and obese BMI values, respectively, relative to a normal BMI.

Using these values to compare the two CT scanners, the IMRIS VISIUS iCT reflects a 104%, 220%, and 576% increase in effective dose compared to the Mobius Airo for increasing BMI phantoms. Considering the previously mentioned methods each machine utilizes to define the protocol used for imaging, it would be expected that the VISIUS iCT would deposit a higher dose to organs than the Airo. The significant increase in increasing effective dose is due to the Mobius Airo’s method for modulating scan parameters compared to the more traditional method of the IMRIS VISIUS iCT. This means the Mobius Airo offers a significant effective dose reduction in patients of higher than normal BMI with a potentially corresponding surgically usable image quality.
Utilizing a similar method to compare the C Arms, Table 4.15, Table 4.16, and Table 4.17 display the effective dose and radiation protection details for the Siemens ARCADIS Orbic 3D for superior, inferior, and combined scans, respectively.

Table 4.15: Effective Dose – Siemens ARCADIS Orbic 3D – L1-L3

<table>
<thead>
<tr>
<th></th>
<th>L1-L3</th>
<th>ED (mSv)</th>
<th># Chest X-ray</th>
<th>Eq Natural Bkg (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.11 ± 0.02</td>
<td>1.1</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td>Overweight</td>
<td>0.17 ± 0.01</td>
<td>1.7</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>Obese</td>
<td>0.13 ± 0.02</td>
<td>1.3</td>
<td>15.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.16: Effective Dose – Siemens ARCADIS Orbic 3D – L3-L5

<table>
<thead>
<tr>
<th></th>
<th>L3-L5</th>
<th>ED (mSv)</th>
<th># Chest X-ray</th>
<th>Eq Natural Bkg (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.19 ± 0.02</td>
<td>1.9</td>
<td>22.8</td>
<td></td>
</tr>
<tr>
<td>Overweight</td>
<td>0.23 ± 0.02</td>
<td>2.3</td>
<td>26.6</td>
<td></td>
</tr>
<tr>
<td>Obese</td>
<td>0.15 ± 0.02</td>
<td>1.5</td>
<td>18.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.17: Effective Dose – Siemens ARCADIS Orbic 3D – Combined

<table>
<thead>
<tr>
<th></th>
<th>Combined</th>
<th>ED (mSv)</th>
<th># Chest X-ray</th>
<th>Eq Natural Bkg (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.30 ± 0.03</td>
<td>3.0</td>
<td>35.9</td>
<td></td>
</tr>
<tr>
<td>Overweight</td>
<td>0.39 ± 0.02</td>
<td>3.9</td>
<td>46.1</td>
<td></td>
</tr>
<tr>
<td>Obese</td>
<td>0.28 ± 0.03</td>
<td>2.8</td>
<td>33.1</td>
<td></td>
</tr>
</tbody>
</table>

For simplicity, comparing the overall changes in effective dose of the combined scans for increasing BMI, the Siemens ARCADIS Orbic 3D deposits a 28.3% increase and
a 7.9% decrease in effective dose for overweight and obese BMI representative phantoms, respectively, relative to a phantom of normal BMI.

Repeating the above process for the GE OEC 9900 Elite simulation results yields Table 4.18, Table 4.19, and Table 4.20 below.

**Table 4.18: Effective Dose – GE OEC 9900 Elite – L1-L3**

<table>
<thead>
<tr>
<th>L1-L3</th>
<th>ED (mSv)</th>
<th># Chest X-ray</th>
<th>Eq Natural Bkg (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.28</td>
<td>2.8</td>
<td>32.6</td>
</tr>
<tr>
<td>Overweight</td>
<td>0.42</td>
<td>4.2</td>
<td>49.5</td>
</tr>
<tr>
<td>Obese</td>
<td>0.71</td>
<td>7.1</td>
<td>84.2</td>
</tr>
</tbody>
</table>

**Table 4.19: Effective Dose – GE OEC 9900 Elite – L3-L5**

<table>
<thead>
<tr>
<th>L3-L5</th>
<th>ED (mSv)</th>
<th># Chest X-ray</th>
<th>Eq Natural Bkg (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.16</td>
<td>1.6</td>
<td>19.3</td>
</tr>
<tr>
<td>Overweight</td>
<td>0.35</td>
<td>3.5</td>
<td>41.3</td>
</tr>
<tr>
<td>Obese</td>
<td>0.42</td>
<td>4.2</td>
<td>49.5</td>
</tr>
</tbody>
</table>

**Table 4.20: Effective Dose – GE OEC 9900 Elite – Combined**

<table>
<thead>
<tr>
<th>Combined</th>
<th>ED (mSv)</th>
<th># Chest X-ray</th>
<th>Eq Natural Bkg (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.44</td>
<td>4.4</td>
<td>51.9</td>
</tr>
<tr>
<td>Overweight</td>
<td>0.77</td>
<td>7.7</td>
<td>90.7</td>
</tr>
<tr>
<td>Obese</td>
<td>1.14</td>
<td>11.4</td>
<td>133.6</td>
</tr>
</tbody>
</table>
Comparing the overall changes in effective dose of the combined scans for increasing BMI, the GE OEC 9900 Elite deposits a 74.7% and 157.3% increase in effective dose for overweight and obese BMI representative phantoms, respectively, relative to a phantom of normal BMI. The simulation results reflect a more linear increase in effective dose with increasing BMI.

Overall, the C Arms effective dose is between one and two orders of magnitude lower than the the CT scanners in some cases. Considering the much lower tube potential as well as reduced tube current that the C-Arm operates, as well as the design of tomograms each third degree and a narrower fan angle, the reduction in dose concurs with what was expected.

The corresponding increase in effective dose with BMI was not consistent with the Siemens ARCADIS Orbic 3D. It is likely that two sources contribute to this behavior. First, the exposure rate is so low with the Orbic 3D that statistical variation in the data collected can be relatively high. Second, the proprietary method Siemens utilizes to automatically adjust the scan parameters is unknown. It is possible that potential for fluctuation or variation within those parameters could significantly influence the differences observed with different BMI equivalent phantoms.
4.5 Image Quality

Of interest to the collaborating clinicians was the change in image quality with respect to patient body mass. The Model 701-D phantom consists of three different materials that tested and validated to be representative of bone, soft tissue, and lung [26]. In order to assess this change, the increase in standard deviation of the uniform areas in the central FOV was investigated, recorded, and averaged from the DICOM image output files of the IMRIS VISIUS iCT. As the lung material is not in the FOV during lumbar spine imaging, it was not included in the averages used to develop combined standard deviation. The average of the standard deviations for the two different materials were then combined using the standard formula for error propagation below to determine the overall change in standard deviation values for the images [27].

$$\sigma (M_1 \pm M_2) = \sqrt{\sigma (M_1)^2 + \sigma (M_2)^2} \quad (3.2)$$

An example of the data collection process and DICOM output for the IMRIS VISIUS iCT is displayed below in Figure 4.14. The results of the analysis for the VISIUS iCT are given in Table 4.21.
Relative to the standard deviation of the values within the ROIs selected for bone and soft tissue for a normal BMI equivalent phantom, there was a 39.4% increase for an overweight equivalent phantom and a 79.2% increase for an obese equivalent patient despite the IMRIS VISIUS iCT’s correlative increase in settings and subsequent $\text{CTDI}_{\text{vol}}$ and DLP. In fact, reviewing values from Table 4.6, a 106% increase in $\text{CTDI}_{\text{vol}} / \text{DLP}$
corresponds to a 39.4% increase in noise for an overweight phantom compared to a normal phantom. Similarly, a 322% increase in CTDI\textsubscript{vol} /DLP corresponds to the 79.2% increase in noise for an overweight phantom compared to a normal phantom.

Comparing increasing image quality assessment with corresponding increase in effective does shows the 39.4% increase in overweight phantom standard deviation to a more relatable 32.6% increase in effective dose. Similarly, the 79.2% increase in image standard deviation follows a 93.6% increase in effective dose.

The same assessment was applied to images from the Siemens ARCADIS Orbic 3D and are displayed in Table 4.22 below.

<table>
<thead>
<tr>
<th>Normal</th>
<th>Overweight</th>
<th>Obese</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.2</td>
<td>97.1</td>
<td>163.8</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>3.79</td>
</tr>
</tbody>
</table>

Table 4.22: Image Quality Change with Patient BMI, Siemens ARCADIS Orbic 3D

Relative to the standard deviation of the values within the ROIs selected for bone and soft tissue for a normal BMI equivalent phantom, there was a 125% increase for an overweight equivalent phantom and a 279% increase for an obese equivalent patient which correspond to a 28.3% increase and 7.9% decrease in effective dose.
4.6 Conclusion and Future Work

Of interesting and clinically relevant note is that despite having a wide array of options, most physicians in the orthopedic surgery department utilize the Mobius Airo mobile CT when available. When asked what their motivation was, most responded that the ease of use and user-friendliness of the console on the device made it most convenient for use, and the group seemed to have an overall lack of consideration of other factors, such as image quality, considering that the Brain Lab itself offers automatic guidance during procedures.

Interestingly, because of the method of CTDI\textsubscript{vol} by modulating tube current based off limited user input, the results for the Mobius Airo show an inverse trend compared to a more traditional CT scanner like the VISIUS iCT. In general, specific organ dose decreased with increase in patient BMI, which would be expected when a patient’s size increases but tube potential and effective current time remains fixed.

While the relative increase in dose to organs from the VISIUS iCT compared to the Airo is significant for a phantom representing a patient of normal BMI, the dissimilarities in dose become more apparent when compared to representative phantoms of increasing BMI. All other factors aside, if the Mobius Airo provides adequate image quality for both the clinician and the Mobius Brain Lab, which it was designed to integrate with, then the Mobius Airo offers substantial dose reduction to the patient,
especially in cases where the patient is of higher than normal BMI. Of course, it is necessary to also weigh the potential increase in risk to medical personal from the previously highlighted room survey results.

Based off of the organ dose reduction for patients of higher than normal BMI due to the Mobius Airo’s unique method of modulation tube current for a standardized dose index, this device seems to be the most effective scanner as a compromise between usability for clinical implementation, image quality for Mobius Brain Lab exportation and use, and dose reduction to patient absorbed organ dose. Consideration still exists for the higher relative risk to medical personal that are present in the operation room during use of the scanner. Implementation of the previously mentioned recommendations to medical personal during the use of the scanner should be ensured to preserve radiation worker dose limits from being exceeded.

A potential issue with the Siemens ARCADIC Orbic 3D is the narrow field of view and physician-reported reduced image quality. This corresponds to the overall significantly reduced absorbed dose, but if the corresponding image quality is unusable to physicians, then the dose, no matter how small, is a liability to the patient without the asset of sufficient imaging information. In addition, the longer setup time and scan time of the Orbic 3D also reduces its appeal to physicians. The automated and rapid scan process, as well as the reported qualitative image quality of either CT system has
rendered the Orbic 3D unused in the operating room. We were informed that prior to our series of tests, the device had not been used for the preceding 9 months.

The Siemens ARCADIS Orbic 3D utilizes a proprietary modulation system, but fluctuations from 8 to 12 mA per shot were observed with consistent tube potential throughout all BMI equivalent phantom sizes. Without understanding the modulation method employed by the scanner, it can be determined that there is no corresponding consistent relationship with BMI and effective dose. However, a significant decrease in image quality with increasing phantom BMI was observed both in statistical analysis as well as qualitatively. Figure 4.15 below reflects three 3D reconstructions for increase phantom BMI from left to right. While the image corresponding to a normal BMI phantom may be usable for surgical placement and verification, the remaining reconstructions corresponding to overweigh and obese BMIs show that for patients of higher than normal weight, the Siemens ARCADIS Orbic 3D becomes unusable for surgical purposes.

Figure 4.15: Siemens ARCADIS Orbic 3D Reconstruction
To further expand this comparison, it would be necessary to repeat the analysis on images from Mobius Airo and GE OEC 9900 Elite which are currently not available. However, as both systems are currently used in the operating room, and the Airo is the system that sees preferential use from clinicians, both CT based scanners display appropriate image quality necessary for surgical use. Again, of interesting note is that during initial acceptance testing, when evaluated for traditional diagnostic use, the Mobius Airo failed for both artifacts and high contrast resolution [18].

The scope of this project covers the majority of the first phase of a two phase study. Phase 1 will end with the completion of the image quality analysis on the Mobius Airo and GE OEC 9900 as well as the remaining data collection on the Medtronic O Arm located in the VA Hospital in Durham, NC. With the end of Phase 1, Phase 2 is to begin a collaborative work with industry partners from each respective company to adjust scan parameters to optimize surgical image quality and organ dose.

In the case of the Siemens ARCADIS Orbic 3D, it is possible that with modification of the scan modulation protocols that the Siemens ARACADIS Orbic 3D could render usable 3D reconstruction images in orthopedic surgery. Achieving this could deliver the least absorbed dose to the patient as well as reducing clinical dose received by radiation workers.
Appendix A

Beam Spectra Data for Siemens STRATON X-ray Tube and GE OEC 9900 3D:

**Siemens STRATON X-ray Tube Spectrum @ 80 kVp Tube Potential**

![Graph showing 80 kVp spectrum](image)

**Siemens STRATON X-ray Tube Spectrum @ 100 kVp Tube Potential**

![Graph showing 100 kVp spectrum](image)
Siemens STRATON X-ray Tube Spectrum @ 120 kVp Tube Potential

Siemens STRATON X-ray Tube Spectrum @ 140 kVp Tube Potential
Siemens ARCADIS Orbic 3D SpekCalc Beam Spectrum @ 83 kVp
GE OEC 9900 Elite SpekCalc Beam Spectrum @ 75 kVp

SpekCalc Predicted Effective Energy & HVL of GE OEC 9900 [24]

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Mean Energy</td>
<td>46.6 keV</td>
</tr>
<tr>
<td>1st HVL</td>
<td>4.25 mm Al</td>
</tr>
<tr>
<td>2nd HVL</td>
<td>5.40 mm Al</td>
</tr>
</tbody>
</table>
References


