Establishing low-energy x-ray fields and determining operational dose equivalent conversion coefficients

Thesis for Master of Science in Medical Radiation Physics

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2008-01-23
ABSTRACT

Reference radiation fields for x-ray qualities are described by the International Organization of Standards (ISO). This study describes the procedure to establish nine different low energy X-ray qualities at the national metrology laboratory, Swedish Radiation Protection Authority, following the document ISO 4037. Measurements of tube voltage, half-value layer, mean energy and spectral resolution have been performed for qualities N-15, N-20, N-25, N-30, N-40, L-20, L-30, L-35 and L-55. Furthermore, dose equivalent conversion coefficients for operational quantities ambient dose equivalent, personal dose equivalent and directional dose equivalent have been calculated by folding the mono-energetic conversion factors with measured spectral distributions of the x-ray qualities. The spectral distributions were unfolded from pulse-height distributions to photon distributions using simulated data of the semiconductor detector used for measurements, generated with the Monte Carlo code PENEOPE.
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1 INTRODUCTION

In Sweden, the Swedish Radiation Protection Authority (SSI) regulates that instruments used for monitoring and measuring ionizing radiation shall be calibrated by an approved laboratory. Calibration ensures that radiation environments are well known and can be regulated; consequently, an effective radiation protection can be sustained. SSI also regulates the interval between calibrations, i.e. calibration of at least one reference instrument every second year for radiotherapy, and calibration every third year for other instruments. The ionizing national metrology laboratory (RMP), located at SSI, is the only laboratory performing approved calibrations in Sweden.

To guarantee that determinations of ionizing dosimetry units are accurate, there are primary standard dosimetry laboratories (PSDL) in about 20 countries worldwide (Podgorsak, 2005). Regular comparisons between the PSDL ensure international consistency of dosimetry standards. The PSDL calibrate secondary standard dosimeters for secondary standard dosimetry laboratories (SSDL), which in turn calibrate instruments used in daily routines in hospitals and industries. RMP, an SSDL, preserves the Swedish national standards for air-kerma, absorbed dose, and the operational dose quantities. The therapy standards at RMP are traceable to the primary laboratory Bureau International des Poids et Measures, France, and the standards for diagnostics and radiation protection are traceable to the primary laboratories Physikalisch-Technische Bundesanstalt, Germany, or National Physics Laboratory, England.

At RMP calibration for photon energies from 8 keV to 1.25 MeV and dose-rate levels from background to radiotherapy levels are available. Concerning x-rays, RMP offers 43 different qualities with different filtrations and generating voltages between 10 and 250 kV. The aim of this study is to expand the number of qualities at RMP to include additional low-energetic qualities, 15 – 55 kV, with filtration different from qualities available today. To achieve this, the procedure in the International Organization of Standards (ISO) document ISO 4037 was followed. ISO 4037 includes four different series; low air-kerma rate, narrow spectrum, wide spectrum and high air-kerma rate series. Five x-ray qualities from the ISO narrow spectrum series (N-15, N-20, N-25, N-30 and N-40) and four from the ISO low air-kerma rate series (L-20, L-30, L-35 and L-55) are included in this study. These qualities were chosen since there have been requests from customers to RMP to do calibrations for these qualities. The low air-kerma rate series has harder filtration than the others, resolution between 18 and 22 % and
typical air-kerma rate of 0.3 mGy/h. The narrow spectrum series has resolution between 27 and 37% and typical air-kerma rates of 1 to 10 mGy/h. The typical air-kerma rates are measured with the tube operating at 1 mA, 1 m from the x-ray focus (ISO 4037-1, 1996). The resolution of a spectrum is expressed as a percentage, and is defined by ISO 4037-1 (1996) as $R_e = \frac{\Delta E}{\bar{E}}$, where $\Delta E$ is the full width at half maximum of the spectrum, and $\bar{E}$ is the mean energy of the spectrum. The narrow spectrum series is used for calibration of personal dosimeters, and the low air-kerma rate series is used for calibration of radiation protection instruments. ISO 4037-1 (1996) also treats the wide-spectrum series and the high air-kerma rate series, but these are not included in this study.

For low energy x-ray qualities, calibration for radiation protection quantities ambient dose equivalent, directional dose equivalent and personal dose equivalent is useful when radiation-environments consist of low energies, as is the case with scattered radiation from x-rays in hospitals and industries, e.g. radioscopic examinations. ISO 4037-3 (1999) states directly the conversion factors from air-kerma to dose equivalent quantities for the established x-ray qualities. But, every x-ray distribution, even if it follows the standard reference values, has small discrepancies. The directional dose equivalent conversion coefficients for qualities N-15, N-20, N-25, L-20 and L-30, and ambient dose equivalent conversion coefficients for N-25, N-30, L-20 and L-30 are given with the note “With these radiation qualities, care needs to be taken as variations in energy distribution may have a substantial influence on the numerical values of conversion coefficients” (ISO 4037-3, 1999). To take this into account, the correction factor for each x-ray quality was calculated by folding the air-kerma distribution for each quality with mono-energetic conversion coefficients.

The qualities were established by measuring half-value layers (HVL) to determine the correct filtration for each quality. With correct filtration, spectral measurements were made to determine mean energy and spectral resolution for the qualities. The spectral measurements of pulse-height spectra were unfolded to photon-spectra to separate pulses belonging to the true spectra from pulses originating in the detector and collimator. This was done by simulating the detector with Monte Carlo-calculations to obtain the detector’s response curve as well as knowledge about interactions in the detector and collimator. The simulations were made with the Monte Carlo code PENELOPE. Finally, conversion coefficients for each quality from air-kerma to ambient, directional and personal dose equivalent were calculated. Earlier, Hakanen
et al (2006) established reference radiation fields for the ISO narrow spectrum series qualities N-15, N-20, N-25, N-30 N-40 and N-60, and made measurements of HVL, spectral resolution and mean energy. Hakanen et al also determined conversion factors from air-kerma to dose equivalent quantities in the same manner as in this study, by measuring spectra for the qualities and folding them with mono-energetic conversion factors.

2 MATERIAL AND METHODS

2.1 THE ISO STANDARD

In this study the international standards 4037, developed by the International Organization for Standardization, were followed. ISO 4037-1 (1996) describes characteristics and production methods for establishing x-ray reference radiation. The standard specifies the characteristics of filtered x-ray radiation in terms of tube voltage, mean energy, resolution and HVL. Table 2.1 and Table 2.2 show these specifications for the qualities included in this study. ISO 4037-1 (1996) states that, for both the low air-kerma rate series and the narrow-spectrum series, the mean energy shall be within ±3 %, the resolution within ±10 %, and the tube potential within ±2 % of the values specified in the standard. For qualities L-20, N-15, N-20 and N-25 though, the mean energies shall be within ±5 % and the resolution within ±15 %. If the resolution of a spectrum is 21 % ± 15 % that means that the resolution can vary between 17.9 and 24.2 %.

Table 2.1. Characteristics of the included x-ray qualities of the low air-kerma rate series for x-ray tubes with inherent filtration of 1 mm Be, from ISO 4037-1 (1996).

<table>
<thead>
<tr>
<th>Radiation Quality</th>
<th>Tube potential [kV]</th>
<th>Mean energy [keV]</th>
<th>Resolution [%]</th>
<th>Additional filtration [mm]</th>
<th>1st HVL [mm]</th>
<th>2nd HVL [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-20</td>
<td>20</td>
<td>17</td>
<td>21</td>
<td>2.0 Al</td>
<td>0.42 Al</td>
<td></td>
</tr>
<tr>
<td>L-30</td>
<td>30</td>
<td>26</td>
<td>21</td>
<td>0.18 Cu + 4.0 Al</td>
<td>1.46 Al</td>
<td></td>
</tr>
<tr>
<td>L-35</td>
<td>35</td>
<td>30</td>
<td>21</td>
<td>0.25 Cu</td>
<td>2.20 Al</td>
<td></td>
</tr>
<tr>
<td>L-55</td>
<td>55</td>
<td>48</td>
<td>22</td>
<td>1.2 Cu</td>
<td>0.25 Cu</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2. Characteristics of the included x-ray qualities of the narrow spectrum series, for x-ray tubes with inherent filtration of 1 mm Be, from ISO 4037-1 (1996).

<table>
<thead>
<tr>
<th>Radiation Quality</th>
<th>Tube potential [kV]</th>
<th>Mean energy [keV]</th>
<th>Resolution [%]</th>
<th>Additional filtration [mm]</th>
<th>1st HVL [mm]</th>
<th>2nd HVL [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-15</td>
<td>15</td>
<td>12</td>
<td>33</td>
<td>0.5 Al</td>
<td>0.14 Al</td>
<td>0.16 Al</td>
</tr>
<tr>
<td>N-20</td>
<td>20</td>
<td>16</td>
<td>34</td>
<td>1.0 Al</td>
<td>0.32 Al</td>
<td>0.37 Al</td>
</tr>
<tr>
<td>N-25</td>
<td>25</td>
<td>20</td>
<td>33</td>
<td>2.0 Al</td>
<td>0.66 Al</td>
<td>0.73 Al</td>
</tr>
<tr>
<td>N-30</td>
<td>30</td>
<td>24</td>
<td>32</td>
<td>4.0 Al</td>
<td>1.15 Al</td>
<td>1.30 Al</td>
</tr>
<tr>
<td>N-40</td>
<td>40</td>
<td>33</td>
<td>30</td>
<td>0.21 Cu</td>
<td>0.085 Cu</td>
<td>0.091 Cu</td>
</tr>
</tbody>
</table>
ISO 4037-1 (1996) also gives recommendations for the homogeneity coefficient between the first and second HVL for the narrow-spectrum series; between 0.75 and 1.0. For the low air-kerma rate series no second HVL or homogeneity coefficient is given, since the second HVL does not differ considerably from the first (ISO 4037-1, 1996).

ISO 4037-3 (1999) defines the conversion coefficients from air-kerma to ambient dose equivalent, directional dose equivalent and personal dose equivalent, both for mono-energetic radiation and for qualities included in the different series.

2.2 EQUIPMENT

2.2.1 X-ray machine and beam collimation

The x-ray tube used at RMP is an Yxlon, model MG 325 (4.5-320 kV and 0-22.5 mA) with a 3 mm Be-filter and a voltage generator Yxlon, model MGP41. The beam has diaphragms in accordance with recommendations made by Organisation Internationale de Métrologie Légale, (OIML, 1990). The first diaphragm is placed 84 mm from the x-ray focus, with a thickness of 18 mm, and a radius of 11 mm. The second one is placed 130 mm from the x-ray focus, has a thickness of 12 mm, and a radius of 13 mm. After the second diaphragm a wheel for additional filters is placed. The filter wheel is made of aluminium, with capacity for 71 different filters. After the filter wheel, the third diaphragm is placed, at a distance of 208 mm from the x-ray focus. The third diaphragm is variable; the one used in this study was 23 mm in diameter, with a thickness of 12 mm (Figure 2.1). All diaphragms are made of tungsten. No monitor ion-chamber was used.

![Figure 2.1. Illustration of the diaphragm positions relative the tube focus.](image-url)
2.2.2 Filters and attenuators

The additional filters used are made of aluminium (99.999% purity) or copper (99.99% purity). The thickness of the filters was measured with a Heidenhain digital positioning meter with accuracy of 0.5 µm. The filters show small variations in thickness (<1%) over the filter-area. The measured thickness at the central point of each filter was used. The thickness of the attenuators was earlier determined by Kyllönen and Grindborg (1999) with the digital positioning meter and by means of weighing and measuring the attenuator area. The mean value of the two methods was used as an estimate of the thickness of the attenuators.

2.2.3 Detectors

Three types of detectors were used in this study, one semi-conductor germanium detector, one ion-chamber, and one radiation protection instrument. The semi-conductor detector, used for spectral measurements, is an ORTEC Ge spectrometer (Model No GLP-06165/05P), equipped with a high purity germanium crystal (diameter 6 mm, length 5 mm) and absorbing layer of beryllium (0.127 mm). The semi-conductor detector was calibrated using $^{55}$Fe and $^{241}$Am with photon energies of 5.9 and 59.5 keV, respectively. The calibration was done both before and after the measurements to ensure consistency. The semi-conductor detector is connected to a multi-channel analyzer (MCA). The MCA is an ORTEC DSPEC Pro. For the HVL measurements a “mammography” ion-chamber (RADCAL 10X5-6M) was used. It has a cylindrical sensitive volume (diameter 43.7 mm, thickness 18.0 mm) and a thin (0.7 mg/cm²) window made by aluminized polyester. The RADCAL ion-chamber achieves a flat response for measurements at low energies. For the field uniformity measurements a radiation protection instrument (ion-chamber) was used, Victoreen Model 470A.

2.3 Tube potential

In order to investigate exactly what tube potential was produced by the x-ray machine for a displayed voltage on the instrument panel, a heavy-filtered spectrum for each of the energies included in the study was collected using the semi-conductor detector. The detector was placed 1 m from the x-ray tube, and the spectra were collected for about one hour each to obtain good statistics. X-ray tube currents between 0.5 and 3 mA were used, low enough to keep dead-time losses below 10%.
The delivered tube potential was found from the collected spectrum by extrapolating the linear high-energy part of the spectrum to zero counts (the intersection with the x-axis after subtracting background). The collected spectra are broadened, and the broadening was assumed to have a Gaussian shape. The ideal solution would be to deconvolving the spectra with a Gaussian function, but this cannot be achieved easily due to the noise in the spectra. (Egerton et al, 2005). To be able to do the deconvolving, a noise-reduction algorithm has to be applied, e.g., Lucy-Richardson or Wiener filtering (Egerton et al, 2005). However, since the information about the noise in the spectra was incomplete, and because the pulse-broadening was assumed to have a minor effect on the results, an easier method for disregarding the broadening was applied. The collected spectrum was assumed to be once convolved with a Gaussian function. This spectrum was then convolved with a Gaussian once more, to get a twice convolved spectrum, and then a third time to get a three-times convolved spectrum (Figure 2.2). From the three different spectra, three intersection points were found by extrapolating the linear high-energy part of each spectrum to $y = 0$, which can be seen as red straight lines in Figure 2.2.

![Figure 2.2. Illustration of the deconvolution-method. The red lines are linear fits of the high-energy part of each spectrum and are extrapolated to $y=0$. The spectra are normalized to equal area.](image)

 amounted to have a minor effect on the results, an easier method for disregarding the broadening was applied. The collected spectrum was assumed to be once convolved with a Gaussian function. This spectrum was then convolved with a Gaussian once more, to get a twice convolved spectrum, and then a third time to get a three-times convolved spectrum (Figure 2.2). From the three different spectra, three intersection points were found by extrapolating the linear high-energy part of each spectrum to $y = 0$, which can be seen as red straight lines in Figure 2.2.

![Figure 2.2. Illustration of the deconvolution-method. The red lines are linear fits of the high-energy part of each spectrum and are extrapolated to $y=0$. The spectra are normalized to equal area.](image)
Each convolved spectrum had its own intersection point, and to find the reference voltage of the non-convolved spectrum a straight line was fitted to the three intersection-points and then extrapolated to zero convolutions (Figure 2.3). This point represents the delivered tube potential.

![Graph showing intersection points and linear fit](image)

**Figure 2.3.** A linear fit (red line) was made to the three black intersection voltage points, and then extrapolated to find the intersection point with the x-axis for the non-convolved spectrum. This point represents the reference tube potential.

### 2.4 Half Value Layer and Filtration

The International Commission on Radiation Units and Measurements (ICRU) defines HVL, second HVL and homogeneity coefficient (ICRU 17 1970). A HVL is defined as the thickness of the specified attenuator material that attenuates the beam of radiation to an extent such that the air-kerma rate is reduced to 50 % of its original value. A second HVL is defined as the additional thickness of specified material that reduces the air-kerma rate to 25 % of its original value. The homogeneity coefficient, \( h \), is defined as the ratio of the first half-value layer to the second half-value layer,

\[
h = \frac{1^{st} HVL}{2^{nd} HVL}
\]

(1)

The determination of HVL was done by ion-chamber current measurements with and without attenuators.
2.4.1 Determination of fixed filtration

The inherent filtration can differ for different x-ray tubes, depending on e.g. the x-ray tube, if a monitor chamber is used etc. To be able to make recommendations for additional filtration, ISO 4037-1 (1996) defines the fixed filtration as the inherent filtration of the x-ray tube, plus the amount of extra aluminium filtering that is needed to obtain a fixed filtration equivalent of 4 mm aluminium at 60 kV (ISO 4037-1 1996). According to ISO 4037-1, for qualities L-20, L-30, N-15, N-20, N-25 and N-30, the fixed filtration consists only of the inherent filtration of the x-ray tube. The amount of aluminium needed for the other qualities (L-35, L-55 and N-40) is found in ISO 4037-1 (1996) and is determined by the HVL at 60 kV. To determine the extra filtration needed for RMP’s x-ray machine, the ion-chamber was set up 1 m from the tube focus, with aluminium attenuators approximately 0.5 m from the focus, between the last diaphragm and the ion-chamber (Figure 2.4).

![Figure 2.4. Experimental set-up for the fixed filtration and HVL measurements. The detector is a RADCAL ion-chamber, placed 1 m from the tube focus. The additional filters are only used for the measurements of HVL.](image)

Measurements were made with nine different attenuator thicknesses between 0.12 and 6.12 mm Al at a tube potential of 60 kV. These thicknesses were chosen since the HVL at 60 kV for the x-ray machine at RMP was unknown and the thicknesses cover the range of HVL for which ISO 4037-1 (1996) gives recommendations. To determine the HVL, the ratio between the current measured for each attenuator to the current measured without attenuator was plotted (Figure 2.5).
If the HVL for an x-ray tube is 0.33 mm Al, the inherent filtration is equal to 0.25 mm Al, and 4-0.25=3.75 mm Al needs to be added to obtain correct fixed filtration, according to Table 8 in ISO 4037-1 (1996). As can be seen in Figure 2.5, the HVL for the x-ray machine at 60 kV at RMP is lower than the first measured point, but since ISO 4037-1 (1996) only gives recommendations of extra filtration for HVL at 60 kV between 0.33 and 3.56 mm Al this was not a problem. For the x-ray machine at RMP, with HVL below 0.33 mm Al, it was assumed that 4 mm Al of extra filtration was required to obtain correct fixed filtration. To control this assumption, a measurement for the HVL at 60 kV with 4 mm additional filtration was made, and was found within 5 % of the HVL stated in ISO 4037-1 (1996).

2.4.2 Half value layer measurements

The filtration for the x-ray qualities consists of fixed filtration and additional filtration. For the included x-ray qualities, additional filtration was added according to Table 2.1 and Table 2.2. To determine the HVL, aluminium or copper attenuators representing the HVL were placed between the additional filtration and the ion-chamber in the same arrangement as above (Figure 2.4). For each measurement four attenuators were used, with two slightly thicker and two slightly thinner than the recommended HVL. Ten measurements were made for each attenuator, and currents between 0.2 and 20 pA were registered. The average of the ten measurements was corrected for temperature, pressure and leakage currents. For each x-ray quality an exponential interpolation between the measured current ratios (with and without
attenuators) was made with a least-square method to determine the HVL. The second HVL was measured in similar ways, but with only two attenuators, close to the recommended thicknesses of second HVL.

If the determined first HVL differed more than 5 % from that stated in ISO 4037-1 (1996), then the additional filtration was adjusted and a new set of measurements was made. This procedure was repeated until the HVL for each quality was within 5 % of the HVL given in ISO 4037-1 (1996). If both copper and aluminium filters were used, the copper filters were placed closest to the x-ray tube.

2.5 UNIFORMITY OF THE FIELD

Three requirements are stated in ISO 4037-1 (1996) concerning the uniformity of the field for the x-ray qualities in question.

- The field diameter shall be large enough to irradiate the detector completely
- The air-kerma rate shall not vary more than 5 % over the entire sensitive volume of the detector.
- At a distance two times the radius of the beam plus its penumbra, the air-kerma rate due to scattered radiation shall be less than 5 % of the air-kerma rate along the central axis.

To ensure the first two requirements, measurements at different positions of the field were performed at 1 m from the tube focus. The sensitive volume of the ion-chamber detector has a circular area of 1500 mm$^2$ (radius 21.85 mm). Measurements were performed for a quadratic field area of 14 400 mm$^2$. To account for scattered radiation from the stem of the ion-chamber, two sets of measurements were made. The first had the ion-chamber placed horizontally and the measurements were made in steps of 5 mm vertically (z-direction) and 20 mm horizontally (y-direction). In the next set of measurements, the ion-chamber was placed vertically and the measurements were made with 20 mm steps vertically and 5 mm steps horizontally. The measurements were automatically corrected for pressure. The temperature changes were monitored during the measurements, but since the temperature did not differ enough to have an influence on the results (< 0.2°C), the changes in temperature were ignored.
To verify the last requirement, the relative contribution of scattered radiation was estimated at four places shifted 120 mm from the centre of the field in the y and z-direction. For these measurements the RADCAL ion-chamber could not be used, since the air-kerma rate was too low. Instead, a radiation protection instrument, capable of registering very low currents, was used. The measurements of scattered radiation were made for four qualities; N-15, N-40, L-20 and L-55. These qualities were chosen to cover the energy range of the nine included qualities.

2.6 SPECTRAL MEASUREMENTS AND PENELOPE SIMULATIONS

To calculate the mean energy and spectral resolution as well as the conversion coefficients, spectral distributions was necessary. For each quality, the semi-conductor detector was set up at 2 m from the x-ray target and the detector was collimated with a 1 cm thick lead collimator with a circular opening (2 mm diameter). The 2 m distance was chosen since that is the distance given by ISO 4037-3 (1999) for the conversion coefficients. To avoid high dead-time, low x-ray currents between 0.01 and 0.04 mA were used. The spectra were recorded for about one hour each. To study if the shape of the spectra is affected by the dose-rate, two additional measurements were made for two tube currents for L-55; 0.5 and 5 mA. To minimize dead-time for these currents, the detector was moved 5 m further back from the x-ray machine. The MCA stored the results in 16384 channels with energy between 0.038 and 80.74 keV (according to the energy calibration) with each bin containing approximately 4.92 eV. The collected spectra are pulse-height distributions. The distributions had to be unfolded, i.e. corrected for detector efficiency and corrected for interactions of incident photons with the detector and collimator, to become photon distributions. To be able to make these corrections for efficiency and interactions in the detector, the semi-conductor detector used for the measurements was simulated. Finally, the photon spectra have to be recalculated to air-kerma spectra to calculate the conversion coefficients.

2.6.1 Monte-Carlo simulations

To unfold the distributions, photon spectra data generated with the Monte Carlo code PENELOPE (version 2006) was used, with the main program PENMAIN. PENELOPE does calculations for arbitrary materials and energies between a few hundred eV to 1 GeV. The simulation of electron and positron interactions is divided into hard and soft events. Hard events are events that lead to large angular deviations and/or energy losses whereas soft
events are events that lead to smaller angular deviations and/or energy losses. The hard events are carefully described, and the soft events are described with less detail. This description is called a full class II (mixed) simulation, and is one of the main features with PENELOPE. (Salvat et al, 2001)

2.6.1.1 Input file

The input file for PENELOPE contains information about type of particles, material and geometry for the simulation. In this study, simulations for energies between 5 and 56 keV were made, in steps of one keV. For each of the energies, 5 million photons were simulated. The lead collimator used in the measurements gave a circular 2 mm field at the surface of the detector. To achieve this in the simulations, the opening angle of the photons was 0.02865 degrees at a distance of 2 m from the detector surface.

For each material, some parameters were stated. Salvat et al (2006) describes the parameters, 

\( E_{\text{ABS}} \) is the energy that the particle (electron, photon, or positron) has when it is assumed to be locally absorbed. This is an important parameter because the time that is required to run the simulation is largely dependent on \( E_{\text{ABS}} \). For a high value (in the order of keV) particles are locally absorbed while maintaining a lot of energy, whereas for a low value each particle is followed by the program through many more interactions. To obtain an adjustment between time and transport details, \( E_{\text{ABS}} \) was set to 0.1 keV in the active part of the detector (the active germanium) and 1 keV in all other materials. \( C_1, C_2, W_{CC}, \) and \( W_{CR} \) are all simulation parameters. \( C_1 \) determines the mean free path between hard elastic events, and \( C_2 \) gives the maximum average fractional energy loss in a single step and is effective only at high energies. PENELOPE allows values between 0 and 0.2 for both \( C_1 \) and \( C_2 \), with 0 giving the most detailed simulation. \( W_{CC} \) and \( W_{CR} \) are cut-off energies, \( W_{CC} \) is used for inelastic scatter and \( W_{CR} \) is used as bremsstrahlung cut-off. An energy loss larger than \( W_{CC} \) or \( W_{CR} \) is assumed to be a hard collision and the larger the value of \( W_{CC} \) and \( W_{CR} \), the faster the simulation can be made. But, with too large value the distributions are distorted due to only soft collisions. In this study, \( C_1 = C_2 = W_{CC} = W_{CR} = 0 \) was used for all materials to obtain a maximal detailed description. The last input-parameter is \( D_{\text{max}} \), the maximum step-length used. Here, \( D_{\text{max}} \) was set to ~10% of the material thickness for each material. If a material was used more than once, then \( D_{\text{max}} \) was ~10% of the thinnest part of the material.
The pulses were stored in 600 bins between 50 and 60050 eV, with each bin representing 100 eV. PENELOPE registers all incoming particles in a specified body and returns an output file with the number of particles in each bin.

2.6.1.2 Geometry file

The semi-conductor detector used for spectral measurements was modelled (Figure 2.8). The design of the geometry was based mainly on a schematic drawing of the detector (provided by the manufacturer, Figure 2.6) but also partly on a CT-scan of the detector (Figure 2.7). Due to time constraints the x-ray machine could not be modelled entirely with the anode creating bremsstrahlung. Instead, the simulation started with mono-energetic photons originating 2 m from the detector.

Figure 2.6. Drawing of the semi-conductor detector used to simulate the detector in PENELOPE.
Figure 2.7. CT-scan of the semi-conductor detector. The detector had a white plastic cap on during the scan, which can be seen at the bottom of the figure.

Figure 2.8. The geometry of the semi-conductor detector. Some details are too small to be seen in the figure, i.e., a 0.127 mm thick Be entrance window and the intrinsic layer (0.3 µm) of germanium in front of the active detector part.

The energies used in this work were between 5 and 55 keV, with few particles reaching far into the detector. Only 0.5 % passes through the active part of the detector (5 mm Ge) for
incoming photons with initial energy 60 keV. Consequently, there was no need to model the whole detector.

During the spectral measurements, a lead collimator was used together with the semiconductor detector. In the simulations made to find the efficiency of the detector, the collimator was not included in the geometry, instead the opening angle was chosen so that the field was 2 mm at the surface of the detector. To investigate if the lead collimator had any impact on the simulation results, the collimator was added in the geometry file and one simulation was made for every 5 keV between 15 and 55 keV. The simulations were initially limited to only these energies due to time constraints, each simulation took between 5 and 10 hours. The opening angle was increased to 0.0573 degrees, large enough to also irradiate part of the collimator. The corrections made based on the simulations are principally depending on the number of recorded photons in the peak 9.8705 keV below the simulated energy. The value 9.8705 keV below the simulated energy is an average of the energies for $K_{\alpha 1}$ (9.886 keV) and $K_{\alpha 2}$ (9.855 keV). If the number of photons in this peak would differ a lot when the lead collimator was added, all the simulations (with steps of one keV) would have to be redone. To see if this was the case, the pulse-height spectra from the simulations made with the collimator was studied. The ratio of photons in the peak 9.8705 keV below the simulated energy with the collimator to the ratio of photons in the peak 9.8705 keV below the simulated energy without the collimator can be seen in Figure 2.9.

![Figure 2.9](image.png) Ratio of the number of photons in the peak at 9.8705 keV below the simulated energy with to without the lead collimator as a function of energy. The simulation was done for each 5 keV between 15 and 55 keV to make an initial check if the collimator affected the results.
The ratio of photons in the two different geometries for the peak at 9.8705 keV below the simulated energy, was less than 1 % (Figure 2.9), therefore, the geometry with only the detector and no collimator was used throughout the simulations.

2.6.1.3 Material file

The material file was created based on materials existing in the PENPELOPE database. The material files in the database contain composition data, densities and mean excitation energies for 280 materials, adapted from the database of the ESTAR program (Berger 1992, Salvat et al 2006). The required result for the calculations was the pulse-height distribution from the active part of the detector, made by germanium. The detector has an intrinsic layer also made from germanium. To separate the two germanium-parts, germanium was created twice in the material file and the detection material was the active germanium.

2.6.2 Calculations based on the simulations

From the PENPELOPE simulations, the efficiency of the detector was calculated. The number of pulses registered in the total absorption peak was divided by the total amount of simulated pulses. In this study, the efficiency is both the intrinsic and absolute efficiency, since each emitted photon is incident on the detector. The total absorption peak was defined in this study as the bin containing the simulated energy. The PENPELOPE spectra were simulated for each keV between 5 and 56 keV, and between these points the efficiency was linearly interpolated. The efficiency curve is seen in Figure 2.10, and was used to correct the measured spectra for efficiency. A low-energy cut-off value of 5 keV was used for all recorded spectra to eliminate the noise found in the low energy region.
The main interaction that influences the spectra is photoelectric effect. If the incoming photon interacts with the active part or with the intrinsic layer of the detector, characteristic x-ray is emitted. The energy of the characteristic x-ray is dependent on what atomic shell the interaction takes place. For interactions in the K-shell, the predominant characteristic x-rays are emitted with energies 9.886 \((K_{\alpha 1})\), 9.855 keV \((K_{\alpha 2})\), 10.982 \((K_{\beta 1})\) or 10.975 \((K_{\beta 3})\) (Firestone, 1996). If the characteristic x-rays escape the detector, peaks in the distribution at energies below the simulated energy are shown, Figure 2.11. Due to the bin-width of the simulation, both \(K_{\alpha 1}\) and \(K_{\alpha 2}\) as well as \(K_{\beta 1}\) and \(K_{\beta 3}\) are too close to each other to be dissolved. Therefore, when correcting for \(K_{\alpha 1}\) and \(K_{\alpha 2}\), a mean value of the two at 9.8705 keV was used. In the same way, \(K_{\beta 1}\) and \(K_{\beta 3}\) were approximated with 10.9785 keV.
Figure 2.11. Spectrum generated by PENELOPE. The total absorption peak was defined as the peak containing the simulated energy (here 25 keV). Two peaks caused by photoelectric effect in the detector can be seen at ~10 keV below the simulated peak.

For each included radiation quality, the corrections for photoelectric effect were made in two steps, with correction for one peak in each step. The first correction is described by

$$N(h\nu - 9.8705)_{\text{corr}} = N(h\nu - 9.8705)_{\text{eff}} - f_{h\nu-9.8705} \cdot N(h\nu)_{\text{eff}} \quad (2)$$

With \(h\nu\) ranging from 55 to 15 keV in steps of approximately 4.92 eV, \(N(h\nu)_{\text{eff}}\) is the number of counts in the bin with energy \(h\nu\) (in keV) in the efficiency corrected spectra, and \(f_{h\nu-9.8705}\) is the fraction of photons that come from characteristic x-rays at 9.8705 keV below \(h\nu\) (K\(_\alpha\)). \(N(h\nu-9.8705)_{\text{eff}}\) is the number of counts in the bin with energy \(h\nu-9.8705\) (in keV) in the efficiency corrected spectra. \(N(h\nu-9.8705)_{\text{corr}}\) is the number of counts in the bin with energy \(h\nu-9.8705\) (in keV) in the spectra when they have been corrected for photoelectric effect.

The second correction is similar to the first but corrects for the peak at 10.9785 keV below \(h\nu_{\text{max}}\) (K\(_\beta\)):

$$N(h\nu - 10.9785)_{\text{final}} = N(h\nu - 10.9785)_{\text{corr}} - f_{h\nu-10.9785} \cdot N(h\nu)_{\text{eff}} \quad (3)$$
\( N(h_{-10.9785})_{\text{final}} \) is the number of counts in the bin with energy \( h_{-10.9785} \) (in keV) in the final spectra. The final spectra are the spectra that were used for the calculations of mean energy, spectral resolution and conversion coefficients.

The low-energy cut-off for each spectrum was 5 keV and both corrections were made at approximately 10 keV below the simulated energy. Therefore, calculations only had to be made for energies between 15 and 55 keV.

Together, these two corrections lead to the final spectra. The method of unfolding the spectral distributions was previously described (Seelentag and Panzer 1979, Laitano et al 1990, Chen et al 1984). The method described by Seelentag and Panzer was used, with small modifications. Seelentag and Panzer used the following formula for corrections:

\[
N_t(E_0) = N_m(E_0) - \eta_k(E_0 + 10) \cdot N_t(E_0 + 10) - \frac{\sum_{k} h(E) \cdot N_t(E_k)}{\varepsilon(E)}
\]

where \( N_t \) is the true photon numbers, \( N_m \) is the measured photon numbers (the pulse height distribution), \( \eta_k(E) \) is the K-escape fraction, \( h(E) \) is the correction factor for Compton background, \( \varepsilon(E) \) is the full energy peak efficiency, \( E^* \) is the energy of which \( E_0 \) is the corresponding Compton edge energy and is equal (in keV) to \( (E_0 / 2) + [(E_0^2 / 4) + 255 \cdot 5E_0]^{1/2} \) and \( E_{\text{max}} \) is the maximum energy of the spectrum. In this study, the whole spectrum was corrected for efficiency before the correction for photoelectric effect (K-escape) was made. Also, no correction for Compton-scattering was made, since the amount of Compton interactions is low for energies under 80 keV (Laitano et al 1990). Figure 2.11 also shows two smaller peaks at 9.8705 and 10.9785 keV, resulting from photoelectric effect in the intrinsic layer of the detector. No correction has been made for these peaks, since they only contain 0.5 % of the total number of pulses.

### 2.7 MEAN ENERGY AND SPECTRAL RESOLUTION

The mean energy of a spectrum is defined in ISO 4037-1 (1996) as

\[
\bar{E} = \frac{\int_0^{E_{\text{max}}} \Phi_E E dE}{\int_0^{E_{\text{max}}} \Phi_E dE}
\]
and the spectral resolution is defined as

\[ R_E = \frac{\Delta E}{E} \times 100. \]  \hspace{1cm} (6)

To calculate the spectral resolution, the spectrum width at half maximum, \( \Delta E \), was taken from figures and divided by the mean energy.

### 2.8 Calculations of Dose Equivalent Conversion Coefficients

ICRU report 51 defines operational quantities for area and individual monitoring of external exposures; ambient dose equivalent, directional dose equivalent and personal dose equivalent. Ambient dose equivalent, \( H^*(d) \), is defined as the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at depth \( d \), on the radius opposing the direction of the aligned field (ICRU 51, 1993). The conversion coefficient \( h^*_{K}(10,R) \) was calculated according to Equation 7:

\[
h^*_{K}(10,R) = \frac{\int_{E_{\text{min}}}^{E_{\text{max}}} N(E) \cdot \frac{\mu_{\text{tr}}(E)}{\rho} \cdot E \cdot h^*_{K}(10,E) \cdot dE}{\int_{E_{\text{min}}}^{E_{\text{max}}} N(E) \cdot \frac{\mu_{\text{tr}}(E)}{\rho} \cdot E \cdot dE}
\] \hspace{1cm} (7).

Where \( N(E) \) is the number of photons with energy \( E \), \( \mu_{\text{tr}}/\rho \) is the mass energy transfer coefficient (Higgins et al 1991), \( h^*_{K}(E) \) is the mono-energetic conversion factor for energy \( E \) and \( h^*_{K}(10,R) \) is the conversion coefficient to ambient dose equivalent for radiation quality \( R \).

Directional dose equivalent, \( H(d,\alpha) \), is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at depth \( d \) on a radius in a specified direction, \( \alpha \) (ICRU 51, 1993). The conversion coefficient \( h'_{K}(0.07;\alpha,R) \) was calculated according to Equation 8:

\[
h'_{K}(0.07;\alpha,R) = \frac{\int_{E_{\text{min}}}^{E_{\text{max}}} N(E) \cdot \frac{\mu_{\text{tr}}(E)}{\rho} \cdot E \cdot h'_{K}(0.07,E,\alpha) \cdot dE}{\int_{E_{\text{min}}}^{E_{\text{max}}} N(E) \cdot \frac{\mu_{\text{tr}}(E)}{\rho} \cdot E \cdot dE}
\] \hspace{1cm} (8).

Where \( h'_{K}(0.07;E,\alpha) \) is the mono-energetic conversion factor for energy \( E \) at depth 0.07 mm and angle \( \alpha \).
Personal dose equivalent, \( H_p(d) \), is the dose equivalent in soft tissue at an appropriate depth at an appropriate depth \( d \) below a specified point on the body (ICRU 51, 1993). The conversion coefficient \( h_{pk}(10;R) \) was calculated according to Equation 9:

\[
h_{pk}(10; R) = \frac{\int_{E_{min}}^{E_{max}} N(E) \cdot \frac{\mu_r(E)}{\rho} \cdot E \cdot h_{pk}(10; E) \cdot dE}{\int_{E_{min}}^{E_{max}} N(E) \cdot \frac{\mu_r(E)}{\rho} \cdot E \cdot dE}
\]

(9).

Where \( h_{pk}(10;E) \) is the mono-energetic conversion factor for energy \( E \) at depth 10 mm and angle \( \alpha \). For this study, only \( \alpha = 0^\circ \) was used, both for directional and personal dose equivalent.

3 RESULTS

3.1 TUBE POTENTIAL

The measured and deconvoluted values for the tube voltages are found in Table 3.1. The table also shows deviations between the displayed and measured voltage. All measured tube potentials are found within the ± 2 % limit of ISO 4037-1 (1996).

<table>
<thead>
<tr>
<th>Set voltage [kV]</th>
<th>Measured voltage [kV]</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0</td>
<td>14.9</td>
<td>0.7</td>
</tr>
<tr>
<td>20.0</td>
<td>19.8</td>
<td>1.0</td>
</tr>
<tr>
<td>25.0</td>
<td>24.8</td>
<td>0.8</td>
</tr>
<tr>
<td>30.0</td>
<td>29.9</td>
<td>0.4</td>
</tr>
<tr>
<td>35.0</td>
<td>34.9</td>
<td>0.3</td>
</tr>
<tr>
<td>40.0</td>
<td>39.9</td>
<td>0.3</td>
</tr>
<tr>
<td>55.0</td>
<td>54.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>
3.2 Filtration

The used filtrations are compared to the recommended ones in Table 3.2. The used filtrations gave a HVL at RMP within 5% of the HVL recommended by ISO 4037-1 (1996).

<table>
<thead>
<tr>
<th>Quality</th>
<th>Additional filtration recommended by ISO 4037-1 [mm]</th>
<th>Additional filtration determined in this study [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-20</td>
<td>2.0 Al</td>
<td>1.7 Al</td>
</tr>
<tr>
<td>L-30</td>
<td>0.18 Cu + 4.0 Al</td>
<td>0.15 Cu + 3 Al</td>
</tr>
<tr>
<td>L-35</td>
<td>0.25 Cu</td>
<td>0.25 Cu</td>
</tr>
<tr>
<td>L-55</td>
<td>1.2 Cu</td>
<td>1.19 Cu</td>
</tr>
<tr>
<td>N-15</td>
<td>0.5 Al</td>
<td>0.3 Al</td>
</tr>
<tr>
<td>N-20</td>
<td>1.0 Al</td>
<td>0.8 Al</td>
</tr>
<tr>
<td>N-25</td>
<td>2.0 Al</td>
<td>1.8 Al</td>
</tr>
<tr>
<td>N-30</td>
<td>4.0 Al</td>
<td>4.0 Al</td>
</tr>
<tr>
<td>N-40</td>
<td>0.2 Cu</td>
<td>0.21 Cu</td>
</tr>
</tbody>
</table>

The thicknesses of the filters have an uncertainty of 0.5 µm, resulting from the measurement procedure. The purity of the filters can affect the measurements, 99.99% pure Al and 99.9% pure Cu result in negligible errors (cf Kupfer et al., 1977). Because the purities in this study were 99.999% and 99.99% respectively, the uncertainty due to impurities were negligible.

3.3 Half Value Layer

The measured HVL are compared with tabulated values in Table 3.3.

<table>
<thead>
<tr>
<th>Quality</th>
<th>Measured 1st HVL [mm]</th>
<th>1st HVL ISO 4037-1 [mm]</th>
<th>Deviation [%]</th>
<th>Measured 2nd HVL [mm]</th>
<th>2nd HVL ISO 4037-1 [mm]</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-20</td>
<td>0.432 Al</td>
<td>0.42 Al</td>
<td>2.9</td>
<td>0.187 Al</td>
<td>0.16 Al</td>
<td>17.0</td>
</tr>
<tr>
<td>L-30</td>
<td>1.491 Al</td>
<td>1.46 Al</td>
<td>2.1</td>
<td>0.399 Al</td>
<td>0.37 Al</td>
<td>7.8</td>
</tr>
<tr>
<td>L-35</td>
<td>2.253 Al</td>
<td>2.20 Al</td>
<td>2.4</td>
<td>0.738 Al</td>
<td>0.73 Al</td>
<td>1.1</td>
</tr>
<tr>
<td>L-55</td>
<td>0.248 Cu</td>
<td>0.25 Cu</td>
<td>0.9</td>
<td>1.351 Al</td>
<td>1.30 Al</td>
<td>4.0</td>
</tr>
<tr>
<td>N-15</td>
<td>0.133 Al</td>
<td>0.14 Al</td>
<td>4.7</td>
<td>0.082 Cu</td>
<td>0.084 Cu</td>
<td>2.9</td>
</tr>
<tr>
<td>N-20</td>
<td>0.325 Al</td>
<td>0.32 Al</td>
<td>1.6</td>
<td>0.096 Cu</td>
<td>0.091 Cu</td>
<td>5.6</td>
</tr>
<tr>
<td>N-25</td>
<td>0.651 Al</td>
<td>0.66 Al</td>
<td>1.4</td>
<td>0.738 Al</td>
<td>0.73 Al</td>
<td>1.1</td>
</tr>
<tr>
<td>N-30</td>
<td>1.168 Al</td>
<td>1.15 Al</td>
<td>1.6</td>
<td>1.351 Al</td>
<td>1.30 Al</td>
<td>4.0</td>
</tr>
<tr>
<td>N-40</td>
<td>0.082Cu</td>
<td>0.084Cu</td>
<td>2.9</td>
<td>0.096 Cu</td>
<td>0.091 Cu</td>
<td>5.6</td>
</tr>
</tbody>
</table>

For the narrow spectrum series, an approximate value for the homogeneity coefficient is given in ISO 4037-1 (1996), h = 0.75-1.0. The calculated homogeneity coefficients were in this study between 0.71 and 0.88.
For the HVL measurement, four potential sources of error can be identified; attenuators, beam size, registered current and impurities. The first part is the thickness of the attenuators. Kyllönen and Grindborg (1999) found an uncertainty in the thickness of the attenuators of less than 0.2 %. A 0.2 % uncertainty in the attenuators leads to a maximum uncertainty of 0.4 % in HVL. The beam size also effects the measurements, because the amount of scattered radiation increases with beam size and lowers the HVL. The beam size correction only applies to higher energies, thus this was negligible in this study (cf Kupfer et al, 1977). The determined current has several uncertainties; instability, uncertainty in the measurements both with and without attenuators and uncertainties due to energy dependence of the ion-chamber. This leads to a combined uncertainty in current between 0.5 and 0.05 %, depending on the magnitude of the measured current. Due to current uncertainties, the uncertainty in HVL was estimated to a maximum of 1.7 %. The uncertainty due to impurities in the filters was in the same manner as described above negligible. Considering all potential sources of error, the final uncertainty in HVL was estimated to 1.8 %.

3.4 Uniformity of the Field

The percentage of scattered radiation measured with the radiation protection instrument is below 1 %, except for L-55 (Table 3.4).

Table 3.4. The percentage of scattered radiation from positions defined in section 2.5.

<table>
<thead>
<tr>
<th>Quality</th>
<th>Position 2 [%]</th>
<th>Position 3 [%]</th>
<th>Position 4 [%]</th>
<th>Position 5 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-20</td>
<td>0.19</td>
<td>0.12</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>L-55</td>
<td>1.69</td>
<td>1.38</td>
<td>2.15</td>
<td>1.69</td>
</tr>
<tr>
<td>N-15</td>
<td>0.19</td>
<td>0.13</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>N-40</td>
<td>0.84</td>
<td>0.89</td>
<td>0.68</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Figure 3.1 and Figure 3.2 show measured field profiles of N-25 with the two different detector configurations. Figure 3.3 and Figure 3.4 show the vertical and horizontal beam profiles for the N-25 quality. The blue dotted lines show the 5 % limit for variations in air-kerma rate, and the red dotted lines show the diameter of the ion-chamber. The vertical and horizontal beam profiles as well as the measured field profiles for the other included qualities are appended, Figure A.1 to A.32.
Figure 3.1. Beam profile for N-25. The detector is placed horizontally with measuring points for each 5 mm in the Z-direction and for each 20 mm in the Y-direction.

Figure 3.2. Beam profile for N-25. The detector is placed vertically with measuring points for each 20 mm in the Z-direction and for each 5 mm in the Y-direction.
Figure 3.3. Horizontal beam profile for N-25. The blue line shows the 5% limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure 3.4. Vertical beam profile for N-25. The blue line shows the 5% limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
3.5 **MEAN ENERGY AND SPECTRAL RESOLUTION**

The mean energies and spectral resolution for all x-ray qualities are found in Table 3.5.

<table>
<thead>
<tr>
<th>Quality</th>
<th>Mean energy calculated [keV]</th>
<th>Mean energy ISO 4037-1 [keV]</th>
<th>Spectral resolution estimated [%]</th>
<th>Spectral resolution ISO 4037-1 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-20</td>
<td>17</td>
<td>17</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>L-30</td>
<td>26</td>
<td>26</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>L-35</td>
<td>30</td>
<td>30</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>L-55</td>
<td>48</td>
<td>47</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>N-15</td>
<td>12</td>
<td>12</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>N-20</td>
<td>16</td>
<td>16</td>
<td>36</td>
<td>34</td>
</tr>
<tr>
<td>N-25</td>
<td>20</td>
<td>20</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>N-30</td>
<td>24</td>
<td>24</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>N-40</td>
<td>33</td>
<td>33</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

The calculated values follow the limits given by ISO 4037-1 (1996). The spectral resolution was estimated by a visual inspection of the FWHM of the spectra, and then divided by the mean energy, see equation 6.

3.6 **SPECTRAL MEASUREMENTS AND PENELOPE SIMULATIONS**

Figure 3.5 shows L-55 spectra for different tube currents. For 5 and 0.5 mA, the spectra were recorded at 5 m, and for 0.05 mA, the spectrum was recorded at 1 m from the x-ray tube. The spectra at 5 m have been corrected for 4 m extra attenuation in air.

![Figure 3.5. L-55 spectra for different tube currents. The spectra are normalized to equal height.](image)
To estimate the simulation effects on the spectral distribution and the conversion coefficients, calculations of mean energy, resolution and conversion coefficients were made for the original spectrum, efficiency corrected spectrum and for the final spectrum. The result is presented in Table 3.6.

<table>
<thead>
<tr>
<th></th>
<th>Uncorrected spectrum</th>
<th>Efficiency corrected spectrum</th>
<th>Final spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Energy [keV]</td>
<td>19</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>Resolution [%]</td>
<td>36</td>
<td>36</td>
<td>35</td>
</tr>
<tr>
<td>$h'K(10)$ [Sv/Gy]</td>
<td>0.50</td>
<td>0.50</td>
<td>0.54</td>
</tr>
<tr>
<td>$h'K(0.07;E,\alpha)$ [Sv/Gy]</td>
<td>1.00</td>
<td>1.00</td>
<td>1.04</td>
</tr>
<tr>
<td>$h_{ik}(10;E,\alpha)$ [Sv/Gy]</td>
<td>0.50</td>
<td>0.50</td>
<td>0.54</td>
</tr>
</tbody>
</table>

To further illustrate the changes made based on the PENELOPE simulations, the three different spectra for N-25 are shown in Figure 3.6. All other qualities are appended, Figure A33 to A40.

The shape of the blue and red curve at approximately 5-14 keV is due to interactions in the detector, and disappears after the corrections (yellow line).
3.7 CONVERSION COEFFICIENTS TO DOSE EQUIVALENT QUANTITIES

Table 3.7, Table 3.8 and Table 3.9 show the calculated conversion coefficients from air-kerma to ambient dose equivalent, \( H'(10) \), directional dose equivalent, \( H'(0.07,0) \), and personal dose equivalent, \( H_p(10) \), compared to the conversion coefficients stated by Hakanen et al (2006) and ISO 4037-3 (1999).

Table 3.7. Conversion coefficients \( h_K^*(10) \) from air-kerma to \( H'(10) \) compared with values calculated by Hakanen et al (2006), and values stated for the different qualities in ISO 4037-3 (1999).

<table>
<thead>
<tr>
<th>Quality</th>
<th>( h_K^*(10) ) this study [Sv/Gy]</th>
<th>( h_K^*(10) ) Hakanen et al [Sv/Gy]</th>
<th>( h_K^*(10) ) ISO 4037-3 [Sv/Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-20</td>
<td>0.36</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>L-30</td>
<td>0.83</td>
<td>-</td>
<td>0.90</td>
</tr>
<tr>
<td>L-35</td>
<td>1.06</td>
<td>-</td>
<td>1.08</td>
</tr>
<tr>
<td>L-55</td>
<td>1.48</td>
<td>-</td>
<td>1.61</td>
</tr>
<tr>
<td>N-15</td>
<td>0.12</td>
<td>0.064</td>
<td>-</td>
</tr>
<tr>
<td>N-20</td>
<td>0.30</td>
<td>0.27</td>
<td>-</td>
</tr>
<tr>
<td>N-25</td>
<td>0.54</td>
<td>0.55</td>
<td>0.52</td>
</tr>
<tr>
<td>N-30</td>
<td>0.78</td>
<td>0.78</td>
<td>0.80</td>
</tr>
<tr>
<td>N-40</td>
<td>1.16</td>
<td>1.18</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Table 3.8. Conversion coefficients \( h'K(0.07;0) \) from air-kerma to \( H'(0.07;0) \), compared with values calculated by Hakanen et al (2006), and values stated for the different qualities in ISO 4037-3 (1999).

<table>
<thead>
<tr>
<th>Quality</th>
<th>( h'K(0.07;0) ) this study [Sv/Gy]</th>
<th>( h'K(0.07;0) ) Hakanen et al [Sv/Gy]</th>
<th>( h'K(0.07;0) ) ISO 4037-3 [Sv/Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-20</td>
<td>1.01</td>
<td>-</td>
<td>1.01</td>
</tr>
<tr>
<td>L-30</td>
<td>1.15</td>
<td>-</td>
<td>1.13</td>
</tr>
<tr>
<td>L-35</td>
<td>1.20</td>
<td>-</td>
<td>1.22</td>
</tr>
<tr>
<td>L-55</td>
<td>1.37</td>
<td>-</td>
<td>1.50</td>
</tr>
<tr>
<td>N-15</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>N-20</td>
<td>0.99</td>
<td>1.00</td>
<td>0.99</td>
</tr>
<tr>
<td>N-25</td>
<td>1.04</td>
<td>1.05</td>
<td>1.03</td>
</tr>
<tr>
<td>N-30</td>
<td>1.12</td>
<td>1.11</td>
<td>1.10</td>
</tr>
<tr>
<td>N-40</td>
<td>1.25</td>
<td>1.27</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Table 3.9. Conversion coefficients \( h_p,K(10) \) from air-kerma to \( H_p(10) \) compared with values calculated by Hakanen et al (2006), and values stated for the different qualities in ISO 4037-3 (1999).

<table>
<thead>
<tr>
<th>Quality</th>
<th>( h_p,K(10) ) this study [Sv/Gy]</th>
<th>( h_p,K(10) ) Hakanen et al [Sv/Gy]</th>
<th>( h_p,K(10) ) ISO 4037-3 [Sv/Gy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-20</td>
<td>0.36</td>
<td>-</td>
<td>0.37</td>
</tr>
<tr>
<td>L-30</td>
<td>0.84</td>
<td>-</td>
<td>0.91</td>
</tr>
<tr>
<td>L-35</td>
<td>1.07</td>
<td>-</td>
<td>1.09</td>
</tr>
<tr>
<td>L-55</td>
<td>1.55</td>
<td>-</td>
<td>1.67</td>
</tr>
<tr>
<td>N-15</td>
<td>0.12</td>
<td>0.064</td>
<td>0.06</td>
</tr>
<tr>
<td>N-20</td>
<td>0.29</td>
<td>0.28</td>
<td>0.27</td>
</tr>
<tr>
<td>N-25</td>
<td>0.54</td>
<td>0.56</td>
<td>0.55</td>
</tr>
<tr>
<td>N-30</td>
<td>0.79</td>
<td>0.79</td>
<td>0.79</td>
</tr>
<tr>
<td>N-40</td>
<td>1.17</td>
<td>1.19</td>
<td>1.17</td>
</tr>
</tbody>
</table>

The uncertainty in the conversion coefficients was estimated by Hakanen et al to at least 1.5 %, depending on e.g. stochastic variability in the recorded number of photons, the corrections...
made based on the simulations, the energy calibration of the detector, the uncertainties in the mono-energetic conversion coefficients from photon fluence to air-kerma and to dose equivalent etc. Since the conversion coefficients in this study are derived in the same way as Hakanen et al, the uncertainty of the conversion coefficients in this study is assumed to be in the same order.

4 DISCUSSION

The additional filtration used in this study was adjusted so that the HVL at RMP was within 5% of the values given in ISO 4037-1. Overall, the used filtrations were lower than the recommended ones. This is due to the higher inherent filtration at RMP. ISO 4037-1 (1996) gives recommendations for 1 mm Be inherent filtration, and the inherent filtration at RMP is 3 mm Be. A harder inherent filtration leads to fewer low-energetic photons and thus a need for lower additional filtration to obtain the same HVL. The mean energy and spectral resolution are within the limits stated by ISO 4037-1 (1996). The measurements made for different tube currents show no difference in the shape of the spectrum for currents between 0.05 and 5 mA. The field uniformity also follows the limits stated, with the field irradiating the detector homogeneously and variations in air-kerma not differing more than 5% over the active part of the detector. Inevitable, all the measurements in this study were associated with an uncertainty. When an x-ray quality is presented at RMP, the quantities of interest are the filtration, HVL and conversion coefficients, and therefore these are the uncertainties that have been evaluated. The uncertainties for some quantities, e.g. field uniformity, are largely dependent on the instrument to be calibrated and cannot be generally determined.

The qualities N-40, L-35 and L-55 were established earlier at RMP. For L-35 and L-55, the filtrations and HVL determined in this study are the same as the ones used earlier. For N-40, there is a 3.5% difference between the HVL established earlier and in this study. This difference is explained by a somewhat higher filtration used earlier.

For the low air-kerma rate series the conversion coefficients determined in this study differ up to 9% from those stated in ISO 4037-3 and for the narrow-spectrum series, the deviations are up to 7%, except for N-15, where the deviation is 50%. When comparing the coefficients to those calculated in the same manner by Hakanen et al, the deviations are smaller (up to 4%), except for N-15, where the deviation is 47%. The HVL for N-15 has a 4.7% deviation from
the HVL stated by ISO 4037-1 (1996), and a homogeneity coefficient of 0.71, less than the recommendations made by ISO. This could be one reason for the deviation in the conversion coefficient. Another reason could be that the spectral distribution can differ a lot for this quality which gives rise to differences in conversion coefficients. For N-15, the conversion coefficient for directional dose equivalent, $h'_K$, does not differ from the ISO conversion coefficient, but the coefficients for personal dose equivalent, $h_{p,K}$ and ambient dose equivalent, $h^*_K$ differ up to 50 %. The reason for this could be that the mono-energetic conversion coefficients are given from 5 keV for $h'_K$, whereas from 10 keV for $h_{p,K}$ and $h^*_K$.

5 CONCLUSIONS
The measurements of tube voltage, HVL, field uniformity, mean energy and spectral resolution show good agreement with the values given in ISO 4037-1; hence, the qualities produced at RMP are close to those defined by ISO.

The unfolding method influences the shape of the spectra and the conversion coefficients. If the method of using spectral measurements is to be used when determining conversion coefficients for calibration at RMP, Monte Carlo simulations are necessary. This method of determining conversion coefficients is to prefer since it takes into account the shape of the spectral distributions of the x-ray tube at RMP.
6 ACKNOWLEDGMENTS

Firstly, I would like to thank my supervisors Linda Persson and Jan-Erik Grindborg at the Swedish Radiation Protection Authority for their support, kindness and encouragement. A special thanks to Jan-Erik for taking time to teach me about PENELOPE and to Linda for being patient when it came to writing the thesis. I would also like to thank Christian Iacobaeus and Göran Samuelson at the Swedish Radiation Protection Authority for helping me in the laboratory and for taking interest in my project.

I am thankful to the Department of Medical Radiation Physics at Stockholm University and Karolinska Institutet for lending me the collimator used in this study. Thanks also to Richard Odh at the Department of Hospital Physics at Karolinska University Hospital for help with the CT-scan of the semi-conductor detector and to Gammadata/ORTEC for providing the drawing of the detector. Finally, I am grateful to my father Stig Larsson for linguistic corrections.
7 REFERENCES


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KYLLÖNEN J-E AND GRINDBORG J-E: Calibration in Medical Diagnostic Beams at the Swedish Secondary Standard Dosimetry Laboratory. SSI report no 04, 1999


APPENDIX

Figure A.1. Horizontal beam profile for N-15

Figure A.2. Vertical beam profile for N-15
Figure A.3. Horizontal beam profile for N-15. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure A.4. Vertical beam profile for N-15. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
Figure A.5. Horizontal beam profile for N-20

Figure A.6. Vertical beam profile for N-20
Figure A.7. Horizontal beam profile for N-20. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure A.8. Vertical beam profile for N-20. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
Figure A.9. Horizontal beam profile for N-30

Figure A.10. Vertical beam profile for N-30
Figure A.11. Horizontal beam profile for N-30. The blue line shows the 5% limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure A.12. Vertical beam profile for N-30. The blue line shows the 5% limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
Figure A.13. Horizontal beam profile for N-40

Figure A.14. Vertical beam profile for N-40
Figure A.15. Horizontal beam profile for N-40. The blue line shows the 5 \% limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure A.16. Vertical beam profile for N-40. The blue line shows the 5 \% limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
Figure A.17. Horizontal beam profile for L-20

Figure A.18. Vertical beam profile for L-20
Figure A.19. Horizontal beam profile for L-20. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure A.20. Vertical beam profile for L-20. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
Figure A.21. Horizontal beam profile for L-30

Figure A.22. Vertical beam profile for L-30
Figure A.23. Horizontal beam profile for L-30. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure A.24. Vertical beam profile for L-30. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
Figure A.25. Horizontal beam profile for L-35

Figure A.26. Vertical beam profile for L-35
Figure A.27. Horizontal beam profile for L-35. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure A.28. Vertical beam profile for L-35. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
Figure A.29. Horizontal beam profile for L-55

Figure A.30. Vertical beam profile for L-55
Figure A.31. Horizontal beam profile for L-55. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.

Figure A.32. Vertical beam profile for L-55. The blue line shows the 5 % limit for variation in air-kerma, and the red line shows the diameter of the ion-chamber.
Figure A.33. Illustration of the PENELOPE correction for N-15. The blue line shows the uncorrected spectra, the red line the efficiency corrected spectra and the yellow line the final spectrum.

Figure A.34. Illustration of the PENELOPE correction for N-20. The blue line shows the uncorrected spectra, the red line the efficiency corrected spectra and the yellow line the final spectrum.
Figure A.35. Illustration of the PENELOPE correction for N-30. The blue line shows the uncorrected spectra, the red line the efficiency corrected spectra and the yellow line the final spectrum.

Figure A.36. Illustration of the PENELOPE correction for N-40. The blue line shows the uncorrected spectra, the red line the efficiency corrected spectra and the yellow line the final spectrum.
Figure A.37. Illustration of the PENELOPE correction for L-20. The blue line shows the uncorrected spectra, the red line the efficiency corrected spectra and the yellow line the final spectrum.

Figure A.38. Illustration of the PENELOPE correction for L-30. The blue line shows the uncorrected spectra, the red line the efficiency corrected spectra and the yellow line the final spectrum.
Figure A.39. Illustration of the PENELOPE correction for L-35. The blue line shows the uncorrected spectra, the red line the efficiency corrected spectra and the yellow line the final spectrum.

Figure A.40. Illustration of the PENELOPE correction for L-55. The blue line shows the uncorrected spectra, the red line the efficiency corrected spectra and the yellow line the final spectrum.