Procedural radiation exposure of interventional cardiologists and radiologists
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CHAPTER 4

Effective dose to staff from interventional procedures: estimations from single and double dosimetry

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Abstract
The exposure of eleven physicians performing interventional procedures was measured by means of two personal dosemeters. One personal dosemeter was worn outside the lead apron and an additional under the lead apron. The study was set up in order to determine the added value of a dosemeter worn under the lead apron. With the doses measured, the effective doses of the physicians were estimated using an algorithm for single dosimetry and two algorithms for double dosimetry. The effective doses calculated with the single dosimetry algorithm ranged from 0.11 up to 0.85 mSv in 4 weeks. With the double dosimetry algorithms, the effective doses ranged from 0.02 mSv up to 0.47 mSv. The statistical analysis revealed no significant differences in the accuracy of the effective doses calculated with single or double dosimetry algorithms. It was concluded that the effective dose cannot be considered a more accurate estimate when two dosemeters are used in stead of one.
Introduction

In the Academic Medical Centre (AMC) in Amsterdam, cardiologists and radiologists perform interventional procedures. During these interventional procedures the physicians are exposed to ionising radiation. In the past, the AMC monitored the exposure of the physicians by means of a single dosemeter worn outside their lead apron as recommended by the provider of the personal dosemeters.\(^1\) Over the years the doses of the physicians increased and some doses exceeded 20 mSv per year. Therefore it was decided to provide the physicians with an additional personal dosemeter to estimate the exposure of the physicians under their lead apron as well.

In publication 85 the ICRP recommends the use of two personal dosemeters (double dosimetry) to estimate the effective doses of physicians performing interventional procedures more accurately.\(^2\) Despite the ICRP recommendations, double dosimetry is not common practice in the Netherlands. As in the Netherlands many European physicians use a single personal dosemeter to determine their exposure from interventional procedures.\(^3\)

Recently the Dutch Commission on Radiation Dosimetry (NCS) released a code of practice for the personal dosimetry of professionals wearing a lead apron.\(^4\) In this code of practice the use of a single personal dosemeter outside the lead apron is recommended. In addition to this, conversion factors to calculate effective doses from these measurements are suggested. The NCS recommends single dosimetry as it is their opinion that double dosimetry leads to a higher administrative (and financial) burden while it is questionable whether the accuracy increased by double dosimetry.

In this context the effective doses of the physicians of the AMC were calculated using the doses measured outside the lead aprons as recommended by the NCS. The effective doses were also calculated with algorithms for double dosimetry. The results of these calculations were compared in order to quantify differences between both methods. The purpose of the study was to determine whether additional dose measurements under the lead apron provide supplementary information to estimate the effective doses more accurately. Moreover, the advantages and disadvantages of the single and double dosemeters were reviewed.
Materials and Methods
Starting from 2004 the exposure of 11 physicians (8 radiologists and 3 cardiologists) was monitored by means of two personal dosemeters. All physicians were involved in interventional procedures. The physicians were provided with a personal dosemeter to measure doses outside their lead aprons and an additional dosemeter to measure doses under their lead aprons. Both dosemeters were mounted in a special holder that was fixed to the lead apron. The holder remained in place during the whole study, while the two dosemeters were replaced simultaneously every 4 weeks.

The 11 physicians used lead aprons of 0.25 mm lead equivalent thickness at 100 kVp (Medical Development and Technology B.V, Hilvarenbeek, The Netherlands; Scanflex Medical AB, Täby, Sweden). As the lead aprons had overlapping pieces on the front, the protection of the front of the physicians was 0.50 mm lead equivalence. For practical reasons doses were measured outside and under one layer of 0.25 mm. Besides the lead aprons, the physicians used thyroid collars of 0.50 mm during the interventional procedures.

The personal dosemeters were provided by the Nuclear Research and Consultant Group (NRG, Arnhem, the Netherlands). The dosemeters contained LiF:Ti, Mg (TLD100) detectors. The dosemeters were returned every 4 weeks to NRG for reading out the doses from the dosemeters. The doses were reported as personal dose equivalent at a depth of 10 mm (H\textsubscript{p}(10)). The doses were reported in multiples of 0.01 mSv while doses below 0.005 mSv were reported as <0.01 mSv.

The physicians performed interventional procedures with Philips X-ray systems (Philips Medical Systems, Best, the Netherlands). At the department of Cardiology two Integris H5000 systems and one Allura 9 machine were used. At the department of Radiology two Integris Allura machines were in use.

The doses reported by NRG were used to estimate the effective doses of the physicians. The effective doses were calculated by means of three different algorithms (Table 1). First, the effective doses were calculated using the NCS conversion factor. The conversion factors according to the NCS were applied to the doses measured outside the lead apron. Additionally effective doses were calculated with two
algorithms for double dosimetry. The effective doses were calculated using the NCRP algorithm\textsuperscript{6} and an algorithm described by Clerinx.\textsuperscript{7}

Table 1: The three algorithms used to calculate the effective doses \((E)\) were \(H_{\text{under}}\) is the dose measured under the lead apron and \(H_{\text{outside}}\) the dose measured outside the lead apron.

<table>
<thead>
<tr>
<th>Name</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCS</td>
<td>(H_{\text{outside}} / 5)</td>
</tr>
<tr>
<td>NCRP</td>
<td>(E = 0.5 \times H_{\text{under}} + 0.025 \times H_{\text{outside}})</td>
</tr>
<tr>
<td>Clerinx et. al.</td>
<td>(E = 1.64 \times H_{\text{under}} + 0.058 \times H_{\text{outside}})</td>
</tr>
</tbody>
</table>

The doses reported by NRG as well as the effective doses were statistically analysed using SPSS-software (release 16.0.2 for Windows). The doses outside and under the lead aprons were entered pair wise. Dose pairs with doses under the lead apron exceeding the dose outside the lead aprons as well as dose pairs where either the dose outside or under the lead aprons were missing were excluded from the statistical analysis. Doses reported as \(< 0.01\ \text{mSv}\) were entered as \(0\ \text{mSv}\). In the regression analysis the effective doses calculated with the NCS single algorithm were entered as dependent variables. The effective doses calculated with the algorithms for double dosimetry as well as the individual physicians were entered as independent variables. Effective doses for doses measured under the lead aprons of \(0\ \text{mSv}\) were not included in the regression analysis. Statistical significant differences were set at a level of \(5\%\) \((p = 0.05)\).

Results
In Table 2 the mean and the median of the doses measured outside and under the lead aprons of the physicians are shown. Additionally the \(25^{\text{th}}\) and \(75^{\text{th}}\) percentiles as well as the minimum and maximum doses are displayed in Figures 1 and 2.

The mean doses measured outside the lead aprons ranged from \(0.53\ \text{mSv}\) up to \(4.24\ \text{mSv}\) in 4 weeks while the mean doses under the lead aprons ranged from \(0.01\ \text{mSv}\) to \(0.18\ \text{mSv}\) in 4 weeks. The highest dose measured outside the lead apron was \(16.78\ \text{mSv}\) in 4 weeks, while under the lead apron a dose up to \(1.17\ \text{mSv}\) at maximum was
measured in 4 weeks. The lowest dose measured on both sides of the lead apron was < 0.01 mSv. This was the case for 2.8% of the measurements outside the lead aprons while under the lead apron 22% of the measurements were < 0.01 mSv. Six dose pairs had to be excluded from the statistical analysis. Two dose pairs had to be excluded because of reading problems and 4 dose pairs were excluded as the doses measured under the lead apron were equal to or higher than the doses measured outside the lead apron.

The effective doses of the physicians calculated by means of the three algorithms are shown in Figure 3. The effective doses estimated with the NCS conversion factor were higher than the effective doses calculated with the two algorithms for double dosimetry. The effective doses estimated with the NCS conversion factor ranged from 0.11 up to 0.85 mSv (mean 0.42 mSv). The effective doses calculated with the Clerinx algorithm ranged from 0.05-0.47 mSv (0.29) and the effective doses calculated with the NCRP algorithm varied between 0.02 mSv and 0.17 mSv (mean 0.10).

The weighted least-squares regression analyses (WLS regression) revealed a linear relation between the effective doses calculated with the NCS-single algorithm and the effective doses estimated with the two algorithms for double dosimetry (ANOVA, p<0.05). In Table 3 the regression constants and the regression coefficients are listed. The slope of the regression line for the effective doses according to the NCS algorithm was 4.19 and according to Clerinx 1.50. In both tests no significant difference between physicians were found (ANOVA, p>0.05).

Two-Related-Sample test were performed between the effective doses according to NCS and the effective doses according to double dosimetry (NCRP and Clerinx). For the tests the effective doses according to NCS were divided with the slope of the linear relation between the NCS algorithm and the algorithms for double dosimetry (4.19 for NCS/NCRP and 1.50 for NCS/Clerinx). The two-related-sample tests revealed no significant differences between effective doses calculated from single dose measurements outside the lead apron and effective doses calculated from double dosimetry (Wilcoxon, p > 0.05).
In Figure 4 the effective doses calculated with the NCRP algorithm were plotted against the effective doses calculated according to the NCS algorithm. The effective doses determined with the NCRP algorithm were plotted on the X-axis while those determined with the NCS algorithm are plotted on the Y-axis. The r-squared ($r^2$) value of the plot in figure 4 was 0.86. A similar plot was made for the effective doses calculated with the Clerinx algorithm and the NCS algorithm (Figures 5, $r^2 = 0.81$).

**Table 2**: The number of measuring periods (N), the median doses and the mean doses of 4-weekly measurements outside and under lead aprons.

<table>
<thead>
<tr>
<th>Physician</th>
<th>N (Outside)</th>
<th>Median doses (mSv/4-weeks)</th>
<th>Mean doses (mSv/4-weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outside apron</td>
<td>under apron</td>
<td>Outside apron</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>3.58</td>
<td>0.17</td>
</tr>
<tr>
<td>2</td>
<td>54</td>
<td>1.02</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>2.09</td>
<td>0.07</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>3.56</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>59</td>
<td>1.40</td>
<td>0.06</td>
</tr>
<tr>
<td>6</td>
<td>59</td>
<td>3.09</td>
<td>0.13</td>
</tr>
<tr>
<td>7</td>
<td>42</td>
<td>2.56</td>
<td>0.15</td>
</tr>
<tr>
<td>8</td>
<td>57</td>
<td>4.16</td>
<td>0.10</td>
</tr>
<tr>
<td>9</td>
<td>59</td>
<td>0.41</td>
<td>0.01</td>
</tr>
<tr>
<td>10</td>
<td>58</td>
<td>0.63</td>
<td>0.01</td>
</tr>
<tr>
<td>11</td>
<td>58</td>
<td>1.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Total</td>
<td>454</td>
<td>1.43</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Table 3**: The regression coefficients (B), standard errors, significance levels and 95% confidence intervals of the linear regression model.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Dependent variable</th>
<th>B</th>
<th>Std. Error</th>
<th>Significance ($p &lt; 0.05$)</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCRP</td>
<td>Constant</td>
<td>0.00</td>
<td>0.01</td>
<td>No</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>NCRP</td>
<td>4.19</td>
<td>0.1</td>
<td>Yes</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>Physicians Group</td>
<td>0.00</td>
<td>0.00</td>
<td>No</td>
<td>0.00</td>
</tr>
<tr>
<td>NCS</td>
<td>Constant</td>
<td>0.02</td>
<td>0.02</td>
<td>No</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>Clerinx</td>
<td>1.50</td>
<td>0.04</td>
<td>Yes</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>Physicians Group</td>
<td>0.00</td>
<td>0.00</td>
<td>No</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure 1: Boxplot of the 4-weekly measurements (mSv/4-weeks) outside the lead aprons of physicians. The black lines in the box marks the median, the box demarks the $25^{\text{th}}$ and $75^{\text{th}}$ percentile.

Figure 2: Boxplot of the 4-weekly measurements (mSv/4-weeks) under lead aprons of physicians. The black lines in the box marks the median, the box demarks the $25^{\text{th}}$ and $75^{\text{th}}$ percentiles.
Figure 3: Effective doses (mSv/4-weeks) of the physicians. The black bars represent the effective doses of the physicians by means of the doses measured outside lead aprons (NCS single). The grey and light gray bars represent the effective doses by means of doses measured outside and under lead aprons (NCRP double and Clerinx double).

Figure 4: Effective doses (mSv/4-weeks) according to the algorithm of NCS (single dosimetry) compared with the effective doses according to the NCRP (double dosimetry).
Figure 5: Effective doses (mSv/4-weeks) according to the algorithm of NCS (single dosimetry) compared to the effective doses according to Clerinx et al. (double dosimetry).

Discussion

The doses measured outside the lead apron of cardiologists and radiologists in the AMC are comparable with the doses measured by other authors. The mean annual dose outside the lead aprons of physicians in the AMC was 28 mSv (from 7.02 mSv to 56.16 mSv). Vano et al. reported doses of cardiologists during three consecutive periods of 5 years. In the most recent period (1999 and 2004) the average annual dose was 18 mSv outside the lead apron. Renaud et al. reported an average annual dose of 20-30 mSv outside the lead aprons of cardiologists. Niklason et al. published doses measured outside the lead aprons of radiologists. He reported mean annual doses of 48 mSv. Williams et al. reported mean monthly doses outside the lead aprons of radiologists that ranged from 1.1 to 6.6 mSv. Per year the doses ranged from 13 mSv to 79 mSv. In the present study, the mean dose of the physicians during a measuring period of 4 weeks varied between 0.5 mSv and 4.3 mSv.

The mean annual dose under the lead aprons of cardiologists and radiologists in the AMC was 1.2 mSv. Vano et al. also reported doses measured under the lead aprons.
He reported an average annual dose of 1.4 mSv. Niklason et al. published annual doses of radiologists measured under their lead aprons. They determined a mean annual dose of 0.9 mSv. In the study of Renaud et al. doses under the lead aprons hardly exceeded the minimum reportable value (0.2 mSv) of the TLDs they used. Doses below this value were reported as zero by the dosimetric service. The doses measured in this study were therefore low. Lower than the doses measured under the lead aprons of physicians in the AMC. In the present study the minimal reportable dose was 0.01 mSv. Despite the lower detection level of the TLD’s 21% of the doses measured under the lead aprons were still below the minimal reportable value of 0.01 mSv and were therefore treated as 0 mSv. Williams et al. also reported average monthly doses under the lead aprons of radiologists. He reported doses that varied from 0 up to 0.48 mSv. In the present study average doses in 4 weeks under the lead apron of physicians varied from 0.01 up to 0.18 mSv. The doses measured outside the lead apron were used to estimate the effective doses of the physicians in the AMC. The effective doses were calculated with the NCS conversion factor for single dosimetry. The conversion factor is the same for all exposure circumstances: different tube voltages and variation in irradiation geometry. According to NCS the effective doses will not be underestimated by using the conversion factor. This was confirmed by Franken et al. His research determined the conversion factors to estimate effective doses from single dose measurements outside the lead apron. His study showed that lead aprons of 0.25 mm need conversion factors from 5 up to 63. A factor 5 is the conversion factor used in the NCS algorithm (Table 5).

The effective doses of the physicians in the AMC calculated with the NCS algorithm were higher than the effective doses calculated with the double dosimetry algorithms. The effective doses according to NCS were on an average 4.2 times higher than the effective doses calculated with the NCRP-algorithm and 1.5 times higher than with the Clerinx-algorithm. This underpins the idea that with the NCS algorithm the effective dose is overestimated. On the other hand the double dosimetry algorithms still leads to an overestimation of the effective dose. However, the double dosimetry algorithms also carry the risk of underestimation.
The estimated effective dose calculated with the NCS algorithm was 0.42 mSv. As this might be an overestimation by a factor of 12.6, the average effective dose of the physicians in the AMC range between 0.03 mSv and 0.42 mSv. With the NCRP algorithm an average effective dose of 0.10 mSv was calculated. Taking an overestimation of $2.03^6$ and an underestimation of $3.3^{13}$ into account the average effective dose of the physicians in the AMC ranges between 0.05 mSv and 0.33 mSv. As the algorithm of Clerinx can lead to either an underestimation of the effective dose (10%) or an overestimation (105%), the mean effective dose of the physicians in the AMC (0.29 mSv) actually ranges between 0.13 mSv and 0.32 mSv.

The circumstances under which doses of the present were measured did not completely meet the assumptions for the algorithms. The doses in the present study were measured outside and under a lead apron of 0.25 mm while the front side of the physicians was actually covered with 0.50 mm (two flaps of 0.25 mm). The doses were measured under a single layer of the lead apron as it was practical to leave the special holders for the dosemeters attached to the lead aprons. By mounting the holders on the frontal layer of the lead aprons, the position of the personal dosemeter remained unaltered during the whole study. The doses measured under the lead aprons were therefore higher than the actual exposure of the physicians.

The purpose of the study was to determine whether the doses measured under the lead aprons provide the additional information that is necessary to estimate the effective doses more accurately. In this study, the added value of measurements under the lead aprons could not be demonstrated. In the end, the statistical analysis revealed no significant difference between the effective doses calculated with the algorithm for single dosimetry and the algorithms for double dosimetry. A similar conclusion was earlier reported by present authors based on a study among radiologists.\textsuperscript{14} as well as by Schultz et al.\textsuperscript{15}

The critical comments in the NCS report regarding double dosimetry instead of single dosimetry are endorsed by authors of the present study and all workers who contributed to this study. More discipline is needed when two dosemeters are used: from the physicians, regarding the use of the dosemeters and from the radiation protection advisors, regarding the organisational measures. Moreover attention has to be paid to the labelling system to avoid mixing up personal dosemeters. Mixing up of
the personal dosemeters could not be avoided during this study despite all extra measures taken, like using of special devices and appointing one person to change both dosemeters simultaneously every 4 weeks. As special attention was paid to the physicians involved in this study, the mixing up of the personal dosemeters could always be reversed. But the authors experienced that under normal circumstances this is not always possible. As in this study the personal dosemeters were changed by the same person at the same time, the measurements of the dosemeters always related to the same measuring period and the two personal dosemeters to the same procedures. Without special attention this is not always the case as physicians often unintentionally forget to change their dosemeters on time, at the same time or change them at all.

Of course the use of two personal dosemeters instead of one is more expensive. The extra annual costs for the extra personal dosemeters was € 63.75 per physician in 2009. It is difficult to calculate the cost of the administrative burden: all persons involved in the study were working as radiation protection advisors. They spent more time on this project and less on other points of interest in radiation protection. However, this was not formally registered.
References


