Radiation exposure in interventional cardiology

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RADIATION EXPOSURE
IN
INTERVENTIONAL CARDIOLOGY

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ABSTRACT

In cardiac interventional radiology the applied fluoroscopy time and the used film length pre-eminently determine the resulting doses for patients and workers. From experiments in laboratory conditions and from measurements in actual practice we derived empirical formulas to calculate the kerma-area product which is a direct measure for the patient dose, as a linear function of fluoroscopy time and film length. Values for the kerma-area product per unit fluoroscopy time and per unit film length were measured for the various projections and technical settings during fluoroscopy and during cinematography. The derived empirical formulas were used to calculate the kerma-area product for cardiac angiographic procedures in the clinical practice of a large cardiology department in a major hospital in the Netherlands. The data refer to nearly 3000 cardiac intervention procedures, fifty-fifty divided between cardio-angiography (CAG) and percutaneous transluminal coronary angiography (PTCA). The median value for the kerma-area product over all cardiac procedures is approx. 35 Gy cm². From collected data we have analyzed the distribution of the fluoroscopy time, film length and the kerma-area product for individual cardiologists. Comparison with overall distributions provide essential information for quality assurance and ALARA programs.

INTRODUCTION

Radiation doses for patients and for staff members generally are much higher in interventional radiology than in conventional general radiography. The resulting levels of exposure are pre-eminently determined by the exposure time during fluoroscopy and during cinematography. Specifically in interventional cardiology the variability in fluoroscopy time and in the used film length in operational practice, can be far more important than variations in technical factors, which determine the radiation characteristics and the image quality.

In the framework of optimizing protection of patients and workers, all staff members in a cardiac radiology facility should be aware of the approximate levels of exposure, for patients and for workers, as resulting from the various radiographic projections used. At first this requires some knowledge of resulting doses per unit of exposure time in fluoroscopy and per unit film length in cinematography. Additionally, it requires knowledge of the total fluoroscopy time and the total film length used in the course of a cardiac procedure.
With the objective to assess the correlation between dose levels and fluoroscopy time and film length respectively, we measured the kerma-area product and the personal dose equivalent for various components of interventional procedures in cardiology. The kerma-area product, in the X-ray beam at patient entrance, is a direct measure for the resulting dose of the patient. In the context of optimization studies and quality assurance programs, it is often satisfactory to work with this easily measurable field quantity. Avoiding the use of patient related dose quantities, avoids the many conceptual problems involved. After all, variations in patient dose quantities are proportional to variations in values for the kerma-area product.

Measurements of the operational quantity personal dose equivalent were performed at well-defined reference positions during laboratory experiments. Individual occupational dose estimates for cardiologists in actual practice, can be derived from these measurements, provided that adequate information is available on exposure geometry, distance and shielding.

We first describe the reference protocol for fluoroscopy and cinematography and the phantom that replaced the patient in our experimental setup. Next, we describe the results of our experiments from which we derive simple numerical formulas for the assessment of the kerma-area product at the patient entrance and we report on the application in operational practice.

We try to demonstrate how systematic registration of kerma-area product can serve as a simple but highly effective method for quality assurance in the control of patient exposure in the daily practice of interventional cardiology.

The second part of the report is related to the dose assessment for occupational exposure of cardiologists. A linear correlation with fluoroscopy time and film length for interventional procedures can serve as a simple but highly effective method for quality assurance in the control of patient exposure in the daily practice of interventional cardiology.

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EXPERIMENTAL SET UP

To simulate actual medical practice as closely as possible during our experiments we composed reference protocols for fluoroscopy and cinematography. These are based on detailed data, that were collected in the course of 125 patient procedures (Den Boer et al. 1993). These data were analyzed for exposure time as a function of radiographic projection (gantry setting), X-ray tube potential and image intensifier field size. The resulting reference protocols are summarized in Table 1. The relative time distribution for the various gantry settings is also shown in Figure 2.

During continuous fluoroscopy the tube potential varies between 70 and 110 kVp, with a weighted mean value of 80 kVp. For pulsed fluoroscopy the potential is between 50 and 100 kVp, with a weighted mean value of 68 kVp. Somewhat more than 40% of the exposure time is in "left" projections LAO, LIO, LSO and LAT.

To avoid misunderstanding it must be noted here that in cardiology it is common use to define the projection according to the position of the image intensifier. Identification about what is left and what is right is just opposite as what is common habit for radiologists. They define the projection according to the position of the X-ray tube.

Each gantry setting was subdivided for three sizes of the image intensifier field: 5”, 7” and 9” respectively. For all measurements the focus-detector distance was 1 metre. The focus to skin distance varied between 0.52 and 0.60 metres.

During cine the tube potential varied between 58 and 125 kVp. Here, too, projections were subdivided for image intensifier field size. The weighted tube potential at 5” was 94 kVp; at 7” it was 82 kVp and at 9” it was 63 kVp. Approximately 40% of cine exposure is at 7”; 50% at 5” and the remaining 10% at 9”.

The X-ray generator had a well-defined voltage-to-current [kVp/ma] relationship for each fluoroscopic and cine mode. During continuous fluoroscopy the maximum tube current was 6 ma. During pulsed fluoroscopy the maximum tube current was 200 ma and the pulse frequency was 25 and 12.5 frames per second. The pulse width is 4 milliseconds.

Kerma-area product values for all different projections were determined by direct measurement and by calculation, using an empirical function which was determined by the manufacturer (Hoomaert 1993). Measurements of the personal dose equivalent were performed for various places above a lead apron and under the apron at the cardiologist’s position. A fixed distance of 0.7 metre was chosen between the front of the dummy cardiologist and the iso-centre. Measurements were performed with calibrated TLD dosemeters provided by our approved dosimetry service.

During all experiments we used a perspex (PMMA) phantom to simulate the patient. A self-made phantom was designed in such a way that the automatically adjusted tube settings correspond to realistic values for a standard adult (see Figure 1). The overall dimensions of the phantom are 0.22 m high, 0.4 m long and 0.3 m wide. The phantom consists of three segments: the solid abdominal part (0.22 x 0.15 x 0.3 m), a thoracic component with a mediastinal, cardiac and pulmonary section and a thoracic cage with different thicknesses. The mediastinal and cardiac sections were composed of solid PPMA (0.15 x 0.25 x 0.1 m) while the pulmonary section was simulated by wet sponges. The thoracic cage consists of PMMA plates with lateral parts of 1.5 cm; the anterior plate was 4.5 cm and the posterior plate is 2.0 cm.

During all experiments the iso-centre was at 0.14 m above the table top and 0.1 m cranial to the abdominal component of the phantom and 0.04 m left from the centre.
KERMA-AREA PRODUCT

A basic measurable quantity to describe the total radiation energy imparted to the patient during X-ray examinations is the kerma-area product KAP (Shrimpton et al. 1981, 1984; Kramer et al. 1981). This quantity adequately discounts for radiation quality, fluence and field size. Measurements of the kerma-area product may be accomplished using large-area flat transmission ionization chambers, which can be attached to the collimator of an X-ray tube. It integrates energy fluence over the entire area of the X-ray beam. For direct KAP measurements such instruments have to be calibrated in terms of [Gy cm\(^{-2}\)]. In many practices such transmission ionization chambers are still calibrated in the traditional non-SI unit [R cm\(^2\)]. This unit refers to the traditional similar quantity named exposure-area product. Corresponding values of the air kerma-area product in [Gy cm\(^{-2}\)] can be obtained by dividing the exposure-area product reading in [R cm\(^2\)] by a factor of 114.

KAP values also can be assessed by calculation, provided that detailed information is available on tube potential [kVp], current [mA], beam filtration and beam size. Calculations are complicated by the fact that the X-ray output varies for different types of X-ray generators. In practice numerical assessment of KAP values is only practicable with the use of mathematical fit-functions, that have to be obtained empirically.

Evidently the kerma-area product for an interventional cardiac procedure is proportional to exposure time during fluoroscopy and during cinematography. Taking account of different radiation quality and beam characteristics under fluoroscopy and under cine, the kerma-area product for a full procedure can be approximated by the function:

\[
\text{KAP} = \alpha \text{FT} + \beta \text{CL} \quad \quad \quad \quad \quad (1)
\]

Here, FT represents the cumulative fluoroscopy time expressed in minutes. The total film length CL expressed in metres, is used as an easily measurable indicator for the cumulative exposure time during cine. The coefficient \(\alpha\) represents the effective kerma-area product per minute of fluoroscopy time [Gy cm\(^{-2}\) min\(^{-1}\)]. For a particular procedure this is the time-weighted mean value of the differential contributions to the kerma-area product per unit of fluoroscopy time in the various projections used. Likewise the coefficient \(\beta\) stands for the contribution to the kerma-area product per unit of film length [Gy cm\(^{-2}\) m\(^{-1}\)].

For all different types of projections and usual image intensifier field sizes we have measured the differential values for the kerma-area product per unit fluoroscopy time as well as the differential values of the kerma-area product per unit film length. Results are presented in Table 2. The given values per type of projection already imply averaging over image field size as applied in our reference procedure. The data in Table 2 clearly show that the patient exposure per minute fluoroscopy is significantly higher for the left projections, especially for LIO and LSO gantry settings. The highest differential value (= 10 Gy cm\(^{-2}\) min\(^{-1}\)) was measured for the LIO projection with pulsed fluoroscopy at 25 frames per second.

For a full interventional procedure, the contribution to the kerma-area product from fluoroscopy and from cinematography can now be calculated provided that the fluoroscopy time and film length are known. For continuous fluoroscopy at an average of 80 kVp the contribution to the KAP per minute of fluoroscopy time corresponds with an effective value for \(\alpha = 2.4 \pm 0.5\) Gy cm\(^{-2}\) min\(^{-1}\).

For pulsed fluoroscopy at an average of 68 kVp with 25 frames per second the corresponding value for \(\alpha\) is 3.2 \pm 0.5 Gy cm\(^{-2}\) min\(^{-1}\). Pulsed fluoroscopy with 12.5 frames per second resulted in half this value, because a fixed kVp/\(\text{mA}\) setting was used. For a newly-developed high-output X-ray tube with grid-switched pulsed fluoroscopy at 8 frames per second, the \(\alpha\) value was approximately 0.4 Gy cm\(^{-2}\) min\(^{-1}\).

The measurements under cine conditions refer to 12.5 and 25 frames per second with pulse widths between 3 ms and 8 ms. X-ray generator settings for cine imply approximately the same tube potential, but obviously a much higher current. Multiple measurements for the reference procedure resulted in \(\beta = 0.8 \pm 0.2\) Gy cm\(^{-2}\) per metre of film length.

Measurements in the course of a previous study (Kicken et al., 1988) resulted in values for \(\alpha = 2.5\) and \(\beta = 0.6\). Taking account of this earlier study we decided to apply the fit-function

\[
\text{KAP} = 2.5 \text{FT} + 0.7 \text{CL} \quad \quad \quad \quad \quad (1.1)
\]

to calculate an adequate approximation for the kerma-area product per patient in the course of an interventional procedure. Uncertainties in the coefficients \(\alpha\) and \(\beta\) are estimated to be approximately 50%, subject to the technical modalities during fluoroscopy and cinematography.

Without further comment we note here that the actual values for the coefficients \(\alpha\) and \(\beta\) change with different settings of the "dose-rate" at the input screen of the image intensifier and further depend on actual tube characteristics. The relationship of kerma-area product and tube voltage and current is technically complex and also influenced by the automatic exposure control system. Therefore, actual values for \(\alpha\) and \(\beta\) must be assessed by measurements in practice.

ASSESSMENT OF KERMA-AREA PRODUCT IN HOSPITAL PRACTICE

Systematic registration of fluoroscopy time and film length in hospital practice provides excellent information for ALARA management of patient exposures and quality control of medical performance. Since mid-1991 we have collected such data in the daily practice of a large cardiology department in a major hospital in the
Netherlands. The collected data refer to nearly 3000 cardiac interventional procedures, fifty-fifty divided between coronary angiography and percutaneous transluminal coronary angiography. The observed distribution of fluoroscopy time and film length per procedure is summarized in Figure 3, subdivided for CAG and PTCA. Statistics of the observed distributions are given in Table 4.

Overall fluoroscopy time in PTCA procedures is 20% to 30% longer than in CAG investigations. For film length the ratio is just the opposite. It turns out in practice that mutual differences between fluoroscopy time and film length compensate each other in the resulting kerma-area product per procedure. The distribution of the resulting kerma-area product therefore, does not significantly differ between CAG and PTCA procedures, which is clearly shown in Figure 3c. To obtain KAP values we applied the approximation as given in equation (1.1). From this it can be concluded that in practice both patient exposure as well as occupational exposure per procedure are mutually comparable in magnitude. The mean value over all procedures is ca. 40 Gy cm² with a median of 35 Gy cm². The 20th percentile is ca. 20 Gy cm² and the 80th percentile is 55 Gy cm². The relative standard deviation of the mean value is ca. 60%.

Compared with the situation in 1986-1988 the use of X-ray in cardiac interventional procedures shows a reduction of approximately 30%, expressed in KAP. This roughly means a reduction of collective dose for patients of the same value. Comparison with earlier findings shows that the overall distribution of KAP values shifted to lower values. In this context it is noteworthy to mention that there is a regular feedback towards the cardiologist of our findings in the course of our study. Recommendations were followed to introduce low frequency cine technique (preferably 12.5 frames per second instead of 50 fps), with consecutive reduction in film length for all procedures. Apparently this feedback policy had a positive influence on the working habits of most practitioners. We noted a significant reduction in the overall distribution of fluoroscopy time. Further observation of the distribution of KAP values per procedure shows that within the upper 20% of all procedures which imply the relatively higher exposures, the KAP values and therefore also the individual patient exposures are roughly a factor 2 to a factor 6 more than the overall median value. Another conclusion from our findings is that about 20% of all procedures account for almost half the collective patient dose. Similar conclusions apply to the occupational doses for the cardiologist as will be described hereafter.

Useful information about technical performance of individual cardiologists can be deduced from further statistical data analysis. For this reason we also analyzed the individual frequency distribution for fluoroscopy time and film length as used by each cardiologist. Statistically significant data were collected for 16 cardiologists in the course of 16 months. Their individual data are summarized in Figure 4. The vertical bars represent the observed range between the 20th and 80th percentiles in their individual distributions. Mean values are marked. For each cardiologist the number of procedures is mentioned along the x-axis.

This type of information is very useful for intercollegial comparison in the context of quality assurance programs. Rapid understanding of individual performance follows from comparison of each individual mean value and each 80th percentile with the respective values for the overall distribution. We wish to emphasize that these values in the overall distribution, as measured in actual practice, may serve as a guidance in the formation of a judgement about the quality of individual medical practice. Such guidance should not be regarded as restrictive or prescriptive. Such guidance levels are intended to encourage the radiology staff to become more aware of the radiation exposures involved in the examinations they administer. Comparison with existing guidance for "generally acceptable" exposure levels may encourage them to review individual performance and to take corrective action when patient exposures consistently exceed guidance levels (HHS 1985).

PERSONAL DOSE EQUIVALENT

The operational quantity personal dose equivalent \( H_p(10) \) at 10 mm tissue equivalent depth is the recommended quantity for further assessment of effective dose or the equivalent dose in internal organs or tissues. The personal dose equivalents \( H_p(0.07) \) and \( H_p(3) \) are recommended for further determination of the equivalent dose to skin and eye lenses respectively (ICRP 1990; ICRU 1988).

The personal dose equivalent at various positions above a lead apron and also under the apron, was measured with calibrated TLD personal dosemeters. The measurements were performed under experimental conditions, applying the reference cardiac protocols for fluoroscopy and cinematography as described in a previous paragraph. The data analysis of measurements was focused on finding correlation with fluoroscopy time and film length, using linear regression procedures.

The discussion here only concerns with values for the personal depth dose equivalent at 10 mm depth measured at collar level, outside the lead apron. In the following text we use the symbol \( H_p \) as an abbreviation. All data refer to a reference distance of 0.7 m between the front of the dummy cardiologist and the iso-centre of the X-ray beam. The data represent measurements of the personal dose equivalent at collar level, outside the apron.

For the left projections in fluoroscopy the contribution to the personal dose equivalent per minute exposure time varies between \( 7 \times 10^{-3} \) mSv min\(^{-1}\) for LSO and \( 36 \times 10^{-3} \) mSv min\(^{-1}\) for LIO. The weighted average value over all left projections is \((22 \pm 8) \times 10^{-3} \) mSv min\(^{-1}\). The contribution from all other projections is a factor of 5 to 10 less. These values vary slightly with the field size.
The weighted mean value of the personal dose equivalent per unit fluoroscopy time over all projections, under reference protocol conditions, is 

\((10 \pm 3) \times 10^{-3} \text{ mSv min}^{-1}\).

For the left projections during cine the contribution to Hp per unit of film length was found to be between 

\(3 \times 10^{-3} \text{ mSv m}^{-1}\) for LSO and \(9 \times 10^{-3} \text{ mSv m}^{-1}\) for LIO.

The average value over all left projections is 

\((5 \pm 2) \times 10^{-3} \text{ mSv per metre of film length}\). The contribution from all other projections add up to less than 

\(1 \times 10^{-3} \text{ mSv m}^{-1}\). The weighted mean estimate for all cine-projections is 

\((2.5 \pm 0.8) \times 10^{-3} \text{ mSv m}^{-1}\). Values for Hp per unit of fluoroscopy time and per unit of film length are summarized in Table 3, for the various projections and field sizes.

The relative distribution of the personal dose equivalent measured at collar level, as a function of the various projections, is also shown in Figure 2. These summarized results clearly show that the Hp at collar level is predominantly determined by LAO, LIO, LSO and LAT projections. These projections correspond to approximately 40% of the total contribution. However, the contribution to the personal dose equivalent is roughly 90%. During cinematography the situation is similar. The left and lateral projections occur about 40% of the time, but they cause roughly 80% of the occupational exposure during cine. We repeat here that the projections are defined according to the position of the image intensifier. Identification about what is left and what is right is just opposite as what is common habit for radiologists. They define the projection according to the position of the X-ray tube.

In summary we conclude from our measurements that the personal dose equivalent at collar level can be calculated by the following approximation:

\[ Hp = FT/100 + CL/400 \]  

\((2.1)\)

As before, the fluoroscopy time is expressed in minutes [min] and cine-film length is in metres [m]. Values for the personal dose equivalent then are expressed in millisievert [mSv].

This approximation applies to continuous and pulsed fluoroscopy with 25 frames per second. For pulsed fluoroscopy with 12.5 frames per second we found

\[ Hp = FT/175 + CL/400 \]  

\((2.2)\)

Further analysis of our data results in a rule of thumb for the estimation of the personal dose equivalent directly from the measured or calculated kerma-area product. When the personal dose equivalent is expressed in [mSv] and the kerma-area product in [Gy cm²] this rule of thumb is:

\[ Hp = KAP/250 \]  

\((2.3)\)

These findings are in good agreement with the results of our previous study (Kicken et al. 1988).

PERSONAL DOSE EQUIVALENT FOR CARDIOLOGISTS

The empirical equation (2.1) enables the assessment of the personal dose equivalent at a reference position of 0.7 metres from the iso-centre, when fluoroscopy time and film length are known. Using this fit-function we are able to present the frequency distribution of calculated Hp values for a total of 2856 cardiac procedures. The relative frequency histogram and the cumulative frequency distribution are shown in Figure 5. Statistics for CAG and PTCA procedures separately are summarized in Table 4. All cardiac procedures taken into account, the mean value is 0.16 mSv per procedure with a standard deviation of 0.11 mSv. The median value is 0.14 mSv. We calculated a 80th percentile of 0.21 mSv. The statistics further show that in about 10% of all cardiac procedures the contribution to the personal dose equivalent at the point of reference is more than twice the median value. In the upper 1% of all procedures the calculated Hp value is a factor of 4 to 8 times the median value.

The uncertainty in the calculated values for the personal dose equivalent at reference position is approximately 30%. One must realize that uncertainties in practical circumstances are larger, due to deviations from the assumed reference conditions. On the basis of earlier results from operational personal dosimetry, we provisionally account for a factor of 2 uncertainty up and downwards.

Comparison of the calculated Hp values under reference conditions, with earlier personal dosimetry measurements in operational practice show that calculated values are close to a factor of 2 higher than values as actually measured in practical circumstances (Kicken et al. 1988).

This might be well explained by the fact that under our reference conditions the position of the dosemeters was fixed, while in practice the variations in body orientation in combination with the angular dependent response, result in lower values measured. Comparison of our findings on the personal dose equivalent for cardiologists with other results as reported in literature made clear that our findings are in the upper part of the reported range for mean Hp values at collar level (Reinaud 1992). In our view, however, the significantly lower outcome of some other studies can be easily attributed to the fact that measurements in ordinary daily practice easily underrate the reality when the dosemeters are not worn properly and at all times.

Variations in the personal dose equivalent result from mutual differences in technical performance and working habits between cardiologists. In a similar approach as described earlier for the assessment of the kerma-area product we have analyzed the individual frequency distribution of Hp values on the basis of recorded data on fluoroscopy time and film length for each cardiologist. Mean values per cardiologist varied between 0.12 and
0.21 mSv per procedure. As easily can be interpreted from equation (2.3) the distribution of the personal dose equivalent per procedure is, in a first approximation, similar to the distribution of KAP values. Therefore the mutual differences and similarities in distributions between cardiologists can directly be deduced from Figure 4c.

On the basis of systematic registration of fluoroscopy time and film length we have assessed the accumulated personal dose equivalent at reference position for all cardiologists as a function of their number of patient procedures. The results are shown in Figure 6. Additional to best estimates, with use of equation (2.1) we have assessed the range of uncertainties to approximately 40% as described before. The vertical bars in Figure 6 correspond with these uncertainties in dose estimates. Systematic data registration was performed in the course of 16 months.

In our ALARA program for radiation protection we apply the 80th percentile of the overall distribution of \( H_p \) values per examination - as measured in actual practice - as a reference level for investigation. When the calculated mean \( H_p \) value per procedure for an individual cardiologist exceeds this level, working conditions and working habits are reviewed to find out whether actions can be recommended to reduce the level of occupational exposure, if this can be done without affecting the medical value of the cardiac procedures.

Detailed discussion falls outside the scope of this paper, but we wish to note that such reference levels for investigation better be defined in terms of mean values per procedure and not only on the basis of accumulated personal dose over a monitoring period. An ALARA judgement cannot be detached from the actual number of patient procedures performed.

**ASSESSMENT OF EFFECTIVE DOSE FOR CARDIOLOGISTS**

For radiation protection purposes, the operational quantity personal dose equivalent \( H_p \) is used as an indicator - or if you so wish as a surrogate - for the so-called effective dose of individual workers. This refers more precisely to the value of the personal dose equivalent \( H_p(10) \) defined at 10 mm depth in tissue (ICRU 1988; ICRP 1991) provided that the value refers to a representative position at the surface of the trunk. Unfortunately, only in the special case of uniform external exposure of the total body \( H_p \) values are approximately equal to the effective dose for the individual. In most other situations the effective dose may be considerably different from measured or calculated \( H_p \) values. In exposure situations, as they occur in interventional radiology, the personal dose equivalent at a point of reference outside the lead apron, greatly overestimates the effective dose for the doctor. This is chiefly because the effectiveness of shielding by the apron is not yet taken into account. On the other hand when the point of reference (or measurement) is chosen under the lead apron considerable underestimation is highly probable. The reason here is that the exposure of unshielded or partially shielded organs is overlooked.

Dose assessment in terms of effective dose in such situations is a very complex matter and requires special expertise in radiation protection dosimetry and detailed knowledge of the radiation field characteristics and exposure geometry (Faulkner et al. 1988, 1993; ICRU 1988). For good understanding, one must realize that the operational quantity personal dose equivalent only refers to a dose value at the point of measurement, where on the other hand the concept of effective dose relates to the weighted mean value of the dose distribution over the relevant body organs.

An additional complicating factor in the dose assessment in interventional radiology is the ultimate inhomogeneous character of the radiation field around the patient. Our findings in experimental conditions show a wide dispersion of \( H_p \) values according to the chosen point of reference. The variability, as measured in the course of our experiments under reference protocol conditions, is demonstrated in Figure 7. Roughly speaking there is a variation of a factor of 2 between left and right at the body and also a factor of 2 between high and low at the body. These measurements are in good agreement with earlier experiments (Huyskens et al. 1987, 1988). These variations do not yet account for changes in body orientation during exposure. The real complicating factor in daily practice of interventional cardiology is the continuous change of body orientation. The long and the short of it is that values of the personal dose equivalent are highly dependent on the chosen place at the body. In the daily practice of personal dosimetry this means great variations according to the place at the body where the dosemeter is worn.

Our findings as summarized in Figure 7, underline why "at the collar" above the lead apron is a recommendable position for a personal dosimeter in the practice of interventional radiology. At that position minimal angular variations occur. But what these findings underline much stronger is that so-called single-badge personal dosimetry is highly inaccurate for the dose assessment for doctors in interventional cardiology. We believe that the methodology as described in this paper can be of great added value. Systematic registration of fluoroscopy time and film length enables a more reliable estimate for the dose equivalent at the reference position of the cardiologist then the use of single-badge personal dosimeters.

In the practice of interventional cardiology, the conversion of \( H_p \) measurements to effective dose varies with lead thickness and depends on body orientation in connection with X-ray projection (gantry setting). Another important factor is the size and fit of the lead apron. When a frontal apron or a bad-fit apron is used, a larger part of the body remains unshielded or partially shielded...
than in the case that a good-fit full wrap-around apron is worn. This is of great importance since job analysis showed that the cardiologist can move towards PA-exposure geometry for up to 10% of the total exposure time and that a substantial part of the exposure is in lateral orientation. In the course of other related studies, we have investigated the shielding effectiveness of lead apron in the practice of interventional radiology. Our ongoing studies make use of Monte Carlo calculations for radiation protection dosimetry (ICRU 1988; ICRP 1987; Zankl et al. 1992).

For the exposure situations as they occur for cardiologists in interventional radiology we apply - as a prudent first approach - a reduction factor of 5 for converting Hp measurements into an estimate for the effective dose. Such under the condition that a wrap-around apron of at least 0.25 mm lead equivalent thickness is worn and provided that no trunk exposure to the primary beam occurs. Our ongoing study gives us good reason to expect that this reduction factor of 5 is in fact a prudent estimate. It should be recognized that great precision in such conversion factors cannot be given, without detailed knowledge of the actual exposure conditions. Therefore some conservatism is justified.

It was mentioned before that we recommend that the personal dosimeter in interventional radiology should be worn at collar level outside the apron. This recommendation applies for the so-called single-badge personal dosimetry. We hold strong arguments against positioning of a single dosimeter under the lead apron. It can be shown that values for the personal dose equivalent under the lead apron always significantly underestimate the effective dose. It becomes highly speculative to assess equivalent doses for organs that are not shielded or only partially shielded. Our calculations show that the contribution to the effective dose that results from exposure of unshielded tissue can be quite significant (Huyskens 1994).

In conclusion we wish to emphasize that only in those cases where a good estimate exists for the personal dose equivalent at a well-defined point of reference, outside the lead apron, a reliable assessment of the effective dose is achievable.

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To avoid misunderstanding it must be noted here that in cardiology it is common use to define the projection according to the position of the image intensifier. Identification about what is left and what is right is just opposite as what is common habit for radiologists. They define the projection according to the position of the X-ray tube.

**TABLE 1** Relative time distribution of gantry settings in the reference protocol for fluoroscopy and cinematography (see also Figure 1)

<table>
<thead>
<tr>
<th>PROJECTION</th>
<th>( FT(%) )</th>
<th>( CL(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALL 9&quot;</td>
<td>7&quot;</td>
<td>5&quot;</td>
</tr>
<tr>
<td>Left Anterior Oblique LAO</td>
<td>24.0 2.9 12.3 8.8</td>
<td>21.2 1.4 9.4 10.4</td>
</tr>
<tr>
<td>Left Inferior Oblique LIO</td>
<td>4.3 -- 1.0 3.3</td>
<td>4.7 -- 1.6 3.1</td>
</tr>
<tr>
<td>Left Superior Oblique LSO</td>
<td>7.9 -- 3.4 4.5</td>
<td>13.1 -- 5.3 7.8</td>
</tr>
<tr>
<td>Left Lateral LAT</td>
<td>5.5 -- 1.8 3.7</td>
<td>3.4 -- 0.8 2.6</td>
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<td>Cranial CRA</td>
<td>5.1 -- 1.8 3.3</td>
<td>5 -- 2.4 2.6</td>
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<tr>
<td>Caudal CAU</td>
<td>4.6 -- 1.8 2.8</td>
<td>7.4 -- 3.7 3.7</td>
</tr>
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<td>Frontal FR</td>
<td>14.9 7.4 5.4 2.1</td>
<td>6.2 3.7 2.0 0.5</td>
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<tr>
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<td>10.3 -- 2.5 7.8</td>
<td>11.9 -- 4.1 7.8</td>
</tr>
<tr>
<td>Right Anterior Oblique RAO</td>
<td>16.4 5.8 6.3 4.3</td>
<td>16.9 2.0 8.1 6.8</td>
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<tr>
<td>Right Inferior Oblique RIO</td>
<td>6.4 -- 1.9 4.5</td>
<td>10.1 -- 3.3 6.8</td>
</tr>
<tr>
<td>Rest</td>
<td>0.6</td>
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</tr>
</tbody>
</table>

For various projections, differential values are given for:

- \( \text{KAP} = \text{kerma-area product in [Gy cm}^2\text{]} \)
- \( \alpha = \text{kerma-area product per minute fluoroscopy} \)
- \( \beta = \text{kerma-area product per metre film length} \)

Description of the reference procedure and explanatory information on projections is given in Table 1.

Specification of X-ray "dose rate" settings at the entrance of the image intensifier are:

- continuous fluoroscopy 9": 0.44 7": 0.52 5": 0.7 [\(\mu\text{Gy s}^{-1}\)]
- pulsed fluoroscopy 9": 8.4 7": 19 5": 28 [\(\text{Gy per frame}\)]
- cinematography 9": 70 7": 153 5": 245 [\(\text{Gy per frame}\)]
<table>
<thead>
<tr>
<th>PROJECTION</th>
<th>FLUOROSCOPY</th>
<th>CINE</th>
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<tr>
<td></td>
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<td>Mean</td>
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<tr>
<td>Left Anterior Oblique LAO</td>
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<td>9 5 6 6</td>
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<tr>
<td>Left Inferior Oblique LIO</td>
<td>-- 36 30 32</td>
<td>-- 9 7 8</td>
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<tr>
<td>Left Superior Oblique LSO</td>
<td>-- 17 17 17</td>
<td>-- 5 3 4</td>
</tr>
<tr>
<td>Left Lateral LAT</td>
<td>-- 11 10 11</td>
<td>-- 2 2 2</td>
</tr>
<tr>
<td>Other</td>
<td>-- 2 2 2</td>
<td>0.5 1 1 1</td>
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</tbody>
</table>

Weighted mean over all projections for reference protocol

- Fluoroscopy: $(10 \pm 3) \times 10^{-3}$ mSv min$^{-1}$
- Cine: $(2.5 \pm 0.8) \times 10^{-3}$ mSv m$^{-1}$

**TABLE 3** Measured values for personal dose equivalent $H_p(10)$ at reference position per unit fluoroscopy time and per unit film length for various projections in interventional cardiology.

Values for fluoroscopy are expressed in $10^{-3}$ mSv min$^{-1}$ and values for cine are expressed in $10^{-3}$ mSv m$^{-1}$.

All values refer to measurements at collar level, outside the lead apron, at a reference distance of 0.7 m between the "dummy" cardiologist and the iso-centre of the X-ray beam.

<table>
<thead>
<tr>
<th>Number of patients</th>
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<tr>
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<td>1456</td>
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</table>

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>20th percentile</td>
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<td>12</td>
<td>23</td>
<td>0.09</td>
<td>4</td>
<td>8</td>
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<td>0.08</td>
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<tr>
<td>median</td>
<td>6</td>
<td>28</td>
<td>35</td>
<td>0.14</td>
<td>9</td>
<td>16</td>
<td>34</td>
<td>0.14</td>
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<tr>
<td>80th percentile</td>
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<td>38</td>
<td>53</td>
<td>0.20</td>
<td>16</td>
<td>28</td>
<td>58</td>
<td>0.23</td>
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<tr>
<td>90th percentile</td>
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<td>45</td>
<td>67</td>
<td>0.26</td>
<td>22</td>
<td>37</td>
<td>74</td>
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<tr>
<td>95th percentile</td>
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<td>50</td>
<td>81</td>
<td>0.32</td>
<td>28</td>
<td>47</td>
<td>96</td>
<td>0.37</td>
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<tr>
<td>99th percentile</td>
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<td>65</td>
<td>123</td>
<td>0.48</td>
<td>45</td>
<td>68</td>
<td>141</td>
<td>0.55</td>
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<tr>
<td>maximum</td>
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<tr>
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<td>11</td>
<td>20</td>
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<tr>
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<td>0.09</td>
<td>9</td>
<td>14</td>
<td>27</td>
<td>0.11</td>
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</tbody>
</table>

**TABLE 4** Statistics of distributions in fluoroscopy time FT and film length CL per procedure as observed in the daily practice of a large cardiology department in a major hospital in the Netherlands.

Values for the kerma-area product KAP and the personal (depth) dose equivalent $H_p$ (badge at collar level outside the apron) were calculated with fit-functions (1.1) and (2.1) respectively.
Figure 1 PPMA patient phantom (dimensions: 0.22 x 0.4 x 0.3 m). For further description: see text.

Figure 2 Relative distribution of various projections in applied reference procedures for fluoroscopy (left) and cine (right). The lower pies show the relative contribution to personal dose equivalent at collar level from the various projections.
Figure 3  Histogram of fluoroscopy time, film length and kerma-area product as measured in daily practice in a large cardiology department of a major hospital in the Netherlands. Explanatory information on statistics is summarized in Table 3.

Figure 4  Distributions of fluoroscopy time and film length as used by individual cardiologists. Measurements refer to 1400 CAG procedures and 1456 PTCA procedures. For each cardiologist the corresponding number of procedures is given along the x-as. KAP values were assessed with equation (1.1).
Figure 5  Histogram and cumulative frequency distribution of calculated values for personal depth dose equivalent at collar level outside the apron, per procedure. Hp values were derived using equation (2.1). Statistics are summarized in Table 4.

Figure 6  Accumulated personal dose equivalent Hp(10) at collar level above apron for cardiologists, as a function of their number of patient procedures. Hp values were assessed on the basis of measured fluoroscopy time and film length for each procedure, with use of equation (2.1). Vertical bars correspond with uncertainties in dose estimates (see text). The upper line corresponds with high individual mean for Hp = 0.2 mSv per procedure. The lower line corresponds with a relatively low mean value of 0.1 mSv per procedure.

Figure 7 Measurements of personal dose equivalent Hp(10) at various positions at the body above apron, relative to Hp at mid-collor.