# Correction of the Contribution of Scattered Photon Radiation to the Ionization Chamber Readings During X-Ray Radiation Quality Assessment

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**Abstract**

Reduction of the systematic error when determining the characteristics of the reference X-ray radiation fields is an essential task according to the ISO 4037-1:2019 standard. This task is especially important in dosimetry laboratories when establishing the qualities of reference photon fields. The aim of the study was to develop a method that allows taking into account the contribution of radiation scattered on the filter when determining the half-value layer of the photon field generated by the X-ray unit. Another goal was to reduce the computational cost of determining this contribution.

One of the major contributors to the systematic error in measuring the half-value layer is the radiation scattered on the filter material. The standard recommends that this error should be taken into account in the measurement. But it does not provide any methodology that would do this.

The study investigated the possibility of reducing the contribution of scattered radiation to the ionization chamber readings when assessing the radiation quality of the X-ray unit by the means of half-value layer. The study utilized the ($N$, $H$, $L$) quality series as reference fields according to ISO 4037-1:2019.

Contribution of the scattered radiation to the half-value layer was compensated with the correction coefficients; they were calculated with the FLUKA Monte Carlo software according to the zero-aperture approximation method. Unlike other similar methods, the proposed approach employs kinetic energy released to matter (kerma), to air in this case, as the main value, which, when utilized instead of deposited energy, reduces the program's runtime several fold.

Correctness of the results obtained in this work was verified by comparing the calculated values of the half-value layer with the tabulated ones provided in the ISO 4037-1:2019 standard. The deviation of calculated values from those specified in the standard does not exceed 2 %.

Calculation results showed that the error contributed by scattered radiation to the magnitude of the half-value layer in direct measurements does not exceed 5 %. The use of the air kerma allowed us to significantly reduce the time for calculating the correction coefficients by the factor of 6–16 times with respect to other methods, depending on the radiation quality series. This made it possible to calculate correction factors for the source-detector distance equal to 2.5 meters.

**Keywords:** Monte Carlo method, X-ray apparatus, scattered radiation.

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# Коррекция вклада рассеянного фотонного излучения в показания ионизационной камеры при оценке качества рентгеновского излучения

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Уменьшение систематической погрешности при определении характеристик эталонных полей рентгеновского излучения в соответствии со стандартом ISO 4037-1:2019 является актуальной задачей при установлении качеств излучения в дозиметрических лабораториях. Целью работы являлась разработка метода, позволяющего учесть вклад излучения, рассеянного на фильтре, при определении слоя половинного ослабления поля фотонного излучения, генерируемого рентгеновской установкой, а также уменьшить затраты на определение этого вклада.

Одним из основных факторов, который вносит систематическую погрешность при измерении слоя половинного ослабления, является излучение, рассеянное на материале фильтра. Стандарт рекомендует учёт этой погрешности при проведении измерений, однако не содержит методики, которая позволила бы это сделать.

В работе исследовалась возможность уменьшения вклада рассеянного излучения в отклик ионизационной камеры при оценке характеристик полей излучения рентгеновской установки с помощью измерения слоёв половинного ослабления для *N*-серии, *L*-серии и *H*-серии качеств рентгеновского излучения согласно стандарту ISO 4037-1:2019. Компенсация вклада рассеянного излучения в результаты измерений производилась путём применения корректирующих коэффициентов. Расчёт коэффициентов производился методом нулевой апертуры, реализованным в Монте-Карло программе FLUKA. Основным отличием метода, предложенного в данной работе, является выбор воздушной кермы в качестве расчётной величины отклика компьютерной модели ионизационной камеры на воздействие фотонного излучения. Корректность результатов, полученных в данной работе, проверялась сопоставлением расчётных значений слоёв половинного ослабления с табличными значениями, приведёнными в стандарте ISO 4037-1:2019. Отклонение расчётных значений от указанных в стандарте не превышает 2 %.

Установлено, что погрешность, вносимая рассеянным излучением в величину слоя половинного ослабления при прямых измерениях, не превышает 5 %. Использование воздушной кермы позволило существенно сократить время расчёта коэффициентов коррекции (относительно других методов, где в качестве отклика модели ионизационной камеры используется поглощённая энергия) в 6–16 раз в зависимости от серии качества излучения. Это позволило произвести расчёт поправочных коэффициентов для расстояния источник–детектор, равного 2,5 м.

**Ключевые слова:** Монте-Карло моделирование, рентгеновская установка, рассеянное излучение.

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## Introduction

One of the main, integral characteristics used to assess the quality of X-ray radiation with respect to its penetration ability is the half-value layer (*HVL*). This value represents the thickness of the attenuating material after which the initial intensity of X-ray radiation is reduced by a half. In addition to the first *HVL* (*HVL*1), the second *HVL* value (*HVL*2) gives the thickness of the attenuating material which decreases the initial photon radiation intensity by the total factor of 4. In other words, the initial X-ray intensity is reduced by 4 through the material's attenuating layer of thickness *HVL*1 + *HVL*2.

The estimation procedure for both *HVL*1 and *HVL*2 according to the ISO 4037-1:2019 [1] can be described as follows:

– an ionization chamber (IC) is placed at a chosen distance from the focal spot of the X-ray tube;

– an attenuation plate made of the specified material (or the filter for short) is placed between the IC and the X-ray tube's focal spot;

– the operator can obtain the dependence $I = f(h)$, where $I$ is an IC response, and $h$ is the filter's thickness, with the latter being varied, thus also obtaining the *HVL*1 and the *HVL*2 values from the resulting *I*-curve.

Such approach to estimation of *HVL* values has one minor flaw: the IC catches not only the radiation attenuated by the photon absorption in the filter but it also registers photons scattered by the latter. The amount of scattered photon radiation getting inside the IC depends on the size of the transverse photon field in the area where the filter is located; that causes over-estimation of the IC response. As a consequence, the *HVL*1 and *HVL*2 values obtained by this method are also overestimated. The standard ISO 4037-1:2019 emphases that this contribution should be mitigated for a tube with the potential greater than 100 kV by the means of extrapolation to infinitely small field size, also known as the zero-aperture approximation method. Although the ISO standard stresses the need for such extrapolation, it does not stipulate a method to perform that.

A set of correction factors would make the zero-aperture approximation method possible for a reduction of scattered radiation's effect on *HVL*1 and *HVL*2 estimation. Implementing this by direct, precise, empirical measurements is a rather cumbersome procedure which would be time-consuming and require a lot of iterations; therefore, replacement of direct measurements with Monte Carlo modeling has been proposed [2]. Although that approach greatly simplifies acquisition of the correction factors, it also requires either a significant computer capability or a long processing time.

This paper proposes an improved version of the method presented in [2]. Slight changes to the initial algorithm can significantly reduce the time required for the correction factors to be calculated; that, in turn, makes it possible to implement the method on conventional desktop computers.

## The zero-aperture approximation method

The underlying assumption for this method postulates that the amount of scattered photon radiation to penetrate the IC depends on the transverse photon field size of the X-ray unit in the area of the filter, which, in turn, implies that there is no scattered radiation penetrating the IC in the case when the transverse photon field size approaches zero.

The algorithm proposed for calculating of correction factors with Monte Carlo modeling proceeds as follows:

– With the help of an appropriate simulation package, FLUKA in this case, the user creates a computer model which contains a source of the initial photon radiation, an IC, and a filter.

– The user determines the dependence $I = f(h)$ by varying the filter's thickness for a given transverse photon field size $d$ (the transverse field size is estimated as the transverse diameter of the field at a given distance from the source). An IC response is tentatively defined at this point as a given quantity calculated by the Monte Carlo program; a more rigorous definition is given in the relevant section later in this paper.

– The user calculates *HVL*1 and *HVL*2 with the dependence $I = f(h)$ thus obtained.

– By matching thus obtained values of *HVL*1 and *HVL*2 with the transverse photon field size $d$, the user determines $h_{HVL1} = g(d_1)$ and $h_{HVL2} = g(d_2)$, where $h_{HVL}$ is a *HVL* thickness for a given transverse photon field size $d$. When $d$ approaches zero, the dependence $h_{HVL} = g(d)$ enables calculation of the *HVL* thickness when scattered radiation at $d = 0$ is absent.

– The correction factor can be calculated as the ratio of the *HVL* for a given field size to the *HVL* at $d = 0$: $\alpha_x = h_{HVL(d=0)} / h_{HVL(d=x)}$.

## Monte Carlo modeling

We used the FLUKA software [3, 4] (ver. 4.0.1) as the environment for the Monte Carlo implementation of the zero-aperture approximation method. The model (Figure 1) consists of two conical regions separated by a cylindrical copper filter placed at 50 cm from the source. At 1 m and 2.5 m from the source, there are two cylindrical areas corresponding to the active volume of the IC. The overall shape of the model's geometry makes it possible to cut off radiation that cannot enter the active volume of the IC.

**Figure 1** – Graphical representation of the Monte Carlo model for the *HVL* calculation. IC 1 m and IC 2.5 m correspond to the location of the active volume of the ionization chambers at a distance of 1 m and 2.5 m from the source (created by using FLAIR program [5])

The source is a flat disc 5 mm in diameter, which corresponds to the size of the actual focal spot of the X-ray machine. The photon radiation field has a conical shape with the source at its top. For a given transverse photon field size *d*, the program gradually increases the filter thickness and calculates the IC value. One iteration of the program, a set of calculations for a given field size, is divided into 50 steps. Each subsequent step increases the filter thickness from 0 mm to 5 times the *HVL* in mm (the initial value of the *HVL* is taken from the ISO 4037-1:2019). One iteration yields the dependence $I = f(h)$, which is then approximated by a cubic spline with packages NumPy and SciPy for Python (Figure 2). The program changes the field size *d* and repeats the sequence.

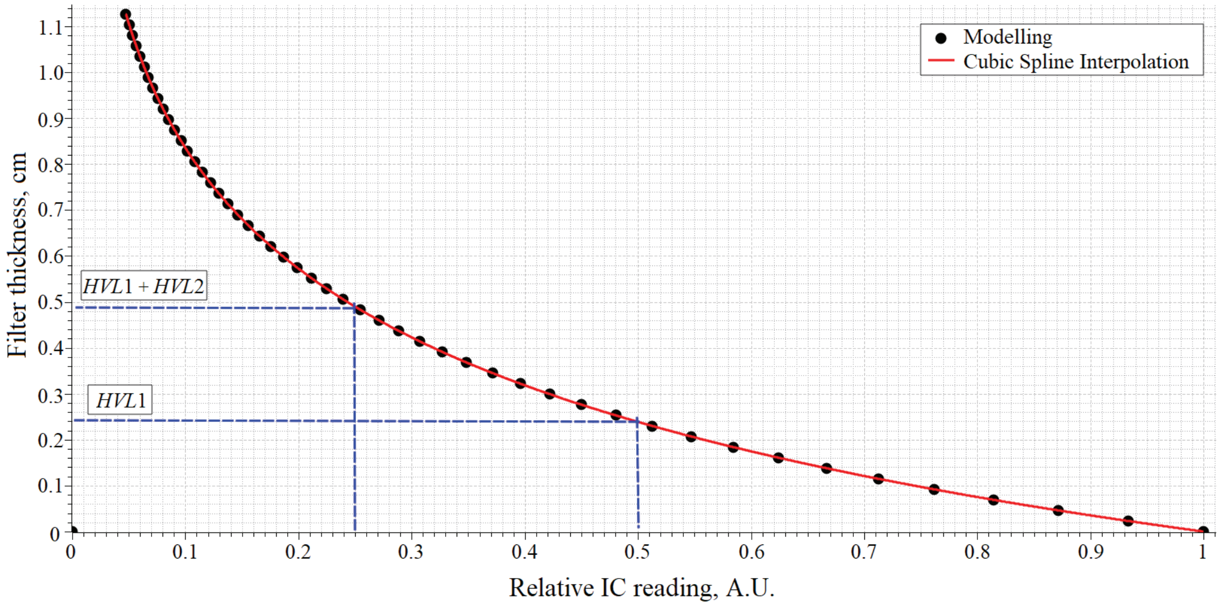

**Figure 2** – The dependence of IC readings from filter thickness with cubic spline interpolation for one iteration. The case for the N150 radiation quality at the distance of 1 m from the source to the IC is shown. The transverse size of the field is 6 cm in diameter at the 50-cm distance from the source

Six iterations was performed for each radiation quality with the following set of transverse field diameters at the 50-cm distance from the source: 6 cm, 7 cm, 8 cm, 9 cm, 10 cm, 11 cm. The intermediate result of one iteration is the set of both *HVL*1 and *HVL*2 values for a given field size. Having completed all six iterations, the program draws the curve $h_{HVL} = g(d)$ for each *HVL*1 and *HVL*2. By making d approach zero, the program calculates $HVL(d = 0)$ and correction factors (Figure 3). The procedure was applied to the *N*-series, the *L*-series, and the *H*-series [6] according to ISO 4037-1:2019.

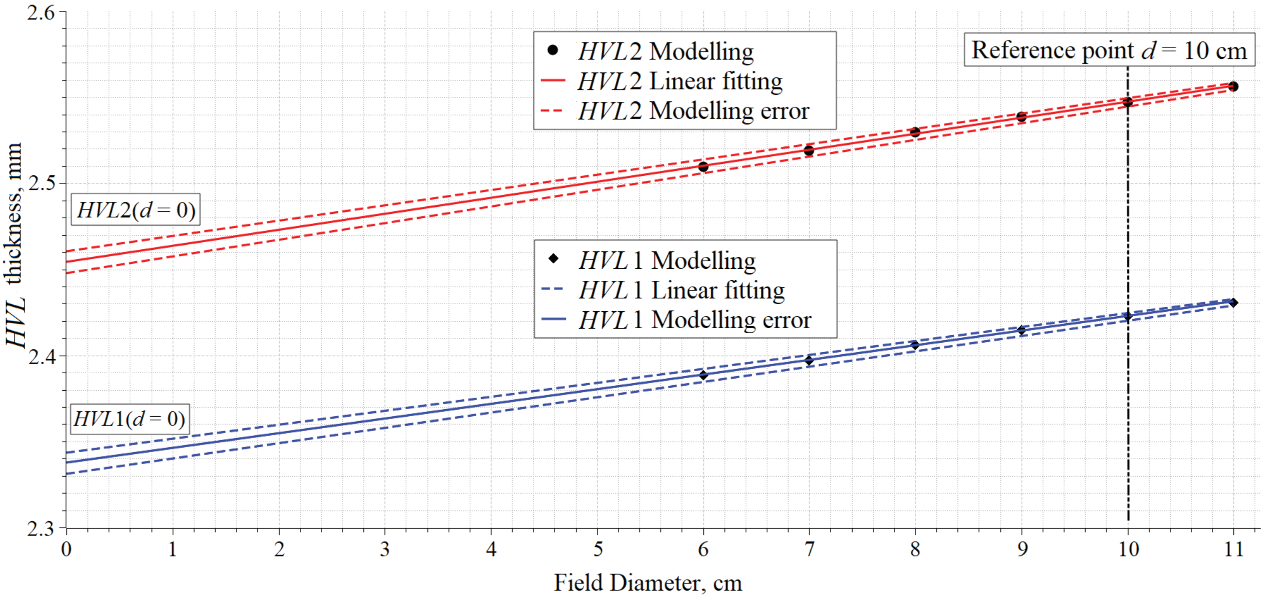

**Figure 3** – The dependence of *HVL* thickness from transverse field diameter: in blue – calculation of *HVL*1, in red – calculation of *HVL*2. The figure shows the case for the N150 radiation quality. The distance between the source and the IC is 1 meter. The transverse dimension of the photon radiation field is 6 cm at a distance of 50 cm from the source

The main improvement which makes increasing the speed of the model's simulations and calculations by several times possible is the choice of the value for the IC response. The study in [2] has suggested previously to use energy deposited inside the active volume of the IC (the tally *F8 of the MCNP program [7]); however, interaction of photon radiation with air molecules is extremely rare due to the fact that air has a very low density (0.0012 g/cm$^3$ according to NIST). Therefore, to collect good statistics and reduce the calculation error, it is necessary for a Monte Carlo simulation to increase the number of primary particles $N$. This leads to a significant increase of the program's runtime because it linearly depends on the number of primary particles, i. e., $t \sim N$ [7], while calculation error has the dependence err $\sim 1/\sqrt{N}$.

Instead of using energy deposited inside the active volume, one can use air kerma as the IC response. That quantity has a simple relation with the photon fluence [8]:

$$K_{air} = \sum_i E_i \varphi_i \left( \frac{\mu_{en}}{\rho} \right)_i , \tag{1}$$

where $\varphi_i$ is photon fluence, 1/cm$^2$; $\left( \frac{\mu_{en}}{\rho} \right)_i$ is the mass energy-absorption coefficient, cm$^2$/g; $E_i$ is the energy of photons, MeV.

The main advantage of using air kerma is the ability to use photon fluence instead of deposited energy when calculating an IC response. With respect to Monte Carlo modelling, the photon fluence is calculated as the ratio of the sum of particle tracks in a given region to the volume of this region. The calculation error does not depend on the number of interactions of photons with air inside the IC with this approach. The modelling discrepancy becomes inversely proportional to the number of photons crossing the given IC volume, which, in turn, makes it possible to reduce the number of simulated primary particles and, thus, the program's runtime.

## Results and discussion

The correction factors calculation was carried out on a personal computer with the following configuration: two Intel Xeon Gold 6138 processors, the DDR4 SDRAM of 84 Gb, the SSD of 512 Gb. Modelling results have been validated by comparing the values for *HVL* at $d = 0$ produced by the program with tabulated values provided for *HVL* in ISO 4037-1:2019. Table 1 shows the results of *HVL* calculations at $d = 0$ using the IC response to deposited energy ($HVL_{st}$) [2] and to air kerma ($HVL_{ak}$).

Simulations were conducted for the source-IC distance at 1 m in both cases. The $HVL_{st}$ calculations were performed for the number of initial particles at $6 \times 10^9$ for the $L$-series and at $16 \times 10^9$ for the $H$-series; the total modelling error for each quality did not exceed 2 %. For the $HVL_{ak}$ calculations, the number of initial particles was $1 \times 10^9$ for both *L*-series and *H*-series with the total modelling error not exceeding 2 % again. This paper does not present the results of comparing $HVL_{st}$ and $HVL_{ak}$ for *N*-series due to anomalously large statistics required to obtain a satisfactory modelling error, i. e., a value equal to three standard deviations and expressed as a percentage of the calculated IC response.

*Table 1*

**Comparison of $HVL(d = 0)$ for radiation qualities in *L*-series and *H*-series (the source-IC distance is 1 m)**

| Quality | $HVL1$ ISO, mm | $HVL1_{st}$, mm | $HVL1_{ak}$, mm | $HVL2$ ISO, mm | $HVL2_{st}$, mm | $HVL2_{ak}$, mm |
|---|---|---|---|---|---|---|
| L70 | 0.483 | 0.479 | 0.483 | 0.505 | 0.507 | 0.504 |
| L100 | 1.22 | 1.214 | 1.214 | 1.25 | 1.245 | 1.25 |
| L125 | 1.98 | 1.992 | 2.012 | 2.02 | 2.076 | 2.049 |
| L170 | 3.4 | 3.404 | 3.417 | 3.46 | 3.497 | 3.476 |
| L210 | 4.52 | 4.576 | 4.530 | 4.55 | 4.533 | 4.571 |
| L240 | 5.19 | 5.224 | 5.226 | 5.22 | 5.274 | 5.217 |
| H80 | 0.176 | 0.177 | 0.178 | 0.268 | 0.268 | 0.270 |
| H100 | 0.294 | 0.293 | 0.295 | 0.462 | 0.463 | 0.463 |
| H150 | 0.808 | 0.801 | 0.811 | 1.21 | 1.203 | 1.220 |
| H200 | 1.54 | 1.536 | 1.554 | 2.28 | 2.286 | 2.303 |
| H250 | 2.42 | 2.448 | 2.441 | 3.24 | 3.276 | 3.279 |
| H300 | 3.22 | 3.200 | 3.254 | 4.00 | 3.976 | 4.042 |

Table 2 shows the correction factors for the aforementioned quality series produced from both the IC response to deposited energy ($HVL_{st}$) [2] and to air kerma ($HVL_{ak}$). The factors were calculated for the transverse diameter of the photon field equal to 10 cm at the 50-cm distance from source.

*Table 2*

**Comparison of correction factors for radiation qualities in *L*-series and *H*-series (the source-IC distance is 1 m; the reference transverse size of the field is 10 cm in diameter at the 50-cm distance from the source)**

| Quality | $\alpha_{st}$ ($HVL1$) | $\alpha_{ak}$ ($HVL1$) | discr, % ($HVL1$) | $\alpha_{st}$ ($HVL2$) | $\alpha_{ak}$ ($HVL2$) | discr, % ($HVL2$) |
|---|---|---|---|---|---|---|
| L70 | 0.988 | 0.984 | 0.407 | 0.992 | 0.984 | 0.813 |
| L100 | 0.974 | 0.974 | 0.000 | 0.964 | 0.971 | 0.721 |
| L125 | 0.957 | 0.967 | 1.034 | 0.985 | 0.965 | 2.073 |
| L170 | 0.955 | 0.962 | 0.728 | 0.967 | 0.96 | 0.729 |
| L210 | 0.972 | 0.962 | 1.039 | 0.955 | 0.961 | 0.624 |
| L240 | 0.959 | 0.964 | 0.519 | 0.971 | 0.962 | 0.936 |
| H80 | 0.989 | 0.989 | 0.000 | 0.989 | 0.989 | 0.000 |
| H100 | 0.983 | 0.987 | 0.405 | 0.989 | 0.983 | 0.610 |
| H150 | 0.974 | 0.978 | 0.409 | 0.96 | 0.970 | 1.031 |
| H200 | 0.961 | 0.971 | 1.030 | 0.958 | 0.962 | 0.416 |
| H250 | 0.969 | 0.966 | 0.311 | 0.962 | 0.963 | 0.104 |
| H300 | 0.949 | 0.964 | 1.556 | 0.954 | 0.964 | 1.037 |

From data Table 1 it can be concluded in that both methods provide similar estimations for *HVL* values with respect to the ones tabulated in ISO 4037-1:2019 with the maximum deviation not exceeding 2 % and the average deviation not exceeding 1 %. For the correction factors in Table 2, it can be noted that the maximum contribution of scattered radiation to the IC response does not exceed 5 %. Using air kerma as the IC reading makes it possible to reduce the calculation time by the factor of 6 for *L*-series and by the factor of 16 for *H*-series. As an example, the total time necessary to calculate $HVL_{st}$ values for *H*-series was approximately four months, while $HVL_{ak}$ calculation took approximately one week. In both those cases, calculations were performed on the same aforementioned PC.

Table 3 gives the final calculation results of the $HVL_{ak}$ and the $\alpha_{ak}$ quantities for the *H*, *L*, and *N* series. Both $HVL_{ak}$ and $\alpha_{ak}$ were calculated for the source-IC distances of 1 m and of 2.5 m and for the transverse diameter of the photon field for $\alpha_{ak}$ being equal to 10 cm at the 50-cm distance from the source.

*Table 3*

***HVL*(*d* = 0) and correction factors for air kerma as IC response for radiation qualities in *L*-series, *H*-series, and *N*-series (the reference transverse size of the field is 10 cm in diameter at the 50-cm distance from the source)**

| Quality | Source-IC distance is 1 m | | | | Source-IC distance is 2.5 m | | | |
|---|---|---|---|---|---|---|---|---|
| | *HVL*1 | *HVL*2 | $\alpha_{HVL1}$ | $\alpha_{HVL2}$ | *HVL*1 | *HVL*2 | $\alpha_{HVL1}$ | $\alpha_{HVL2}$ |
| L70 | 0.483 | 0.504 | 0.984 | 0.984 | 0.483 | 0.506 | 0.991 | 0.993 |
| L100 | 1.214 | 1.250 | 0.974 | 0.971 | 1.215 | 1.257 | 0.984 | 0.986 |
| L125 | 2.012 | 2.049 | 0.967 | 0.965 | 2.013 | 2.050 | 0.979 | 0.977 |
| L170 | 3.417 | 3.476 | 0.962 | 0.960 | 3.416 | 3.473 | 0.974 | 0.971 |
| L210 | 4.530 | 4.571 | 0.962 | 0.961 | 4.515 | 4.576 | 0.970 | 0.975 |
| L240 | 5.226 | 5.256 | 0.964 | 0.962 | 5.217 | 5.254 | 0.974 | 0.973 |
| H80 | 0.178 | 0.270 | 0.989 | 0.989 | 0.181 | 0.273 | 0.994 | 0.996 |
| H100 | 0.295 | 0.463 | 0.987 | 0.983 | 0.299 | 0.468 | 0.994 | 0.992 |
| H150 | 0.811 | 1.220 | 0.978 | 0.970 | 0.816 | 1.226 | 0.989 | 0.981 |
| H200 | 1.554 | 2.303 | 0.971 | 0.962 | 1.558 | 2.31 | 0.979 | 0.976 |
| H250 | 2.441 | 3.279 | 0.966 | 0.963 | 2.449 | 3.272 | 0.978 | 0.970 |
| H300 | 3.254 | 4.042 | 0.964 | 0.964 | 3.257 | 4.035 | 0.974 | 0.973 |
| N100 | 1.093 | 1.153 | 0.975 | 0.975 | 1.096 | 1.157 | 0.986 | 0.987 |
| N120 | 1.682 | 1.748 | 0.969 | 0.968 | 1.687 | 1.750 | 0.986 | 0.98 |
| N150 | 2.337 | 2.454 | 0.965 | 0.963 | 2.340 | 2.455 | 0.983 | 0.976 |
| N200 | 3.941 | 4.019 | 0.962 | 0.961 | 3.937 | 4.009 | 0.977 | 0.971 |
| N250 | 5.129 | 5.190 | 0.964 | 0.963 | 5.121 | 5.185 | 0.973 | 0.973 |
| N300 | 6.013 | 6.058 | 0.967 | 0.965 | 6.009 | 6.061 | 0.977 | 0.976 |

A direct comparison shows that both methods, either using the deposited energy or air kerma as the IC response, yield similar results with respect to both *HVL*(*d* = 0) and the correction factors. The deviation of calculated *HVL* values from those specified in the standard does not exceed 2 %. However, using air kerma as the IC reading is preferable since this method makes the calculations much faster, down by 16 times for selected quality series. This time reduction for the correction factors is especially significant when the distance between the X-ray apparatus's focal spot and the IC is equal to 2.5 m.

The method proposed in this paper has several flaws, however. First of all, in order to use air kerma as the IC response according to formula (1), the mass-energy absorption coefficients must be obtained for every energy value in the photon spectrum. Those coefficients are stored in databases (the NIST database [9] was used for the results in this paper) as a set of tabulated values for a given set of energies. Such a database contains 41 mass-energy absorption coefficients for copper in the energy range between 1 keV and 20 MeV. A typical X-ray spectrum with maximum energy >100 keV contains more than 100 energy bins when properly measured by any modern spectrometer. The necessary mass absorption coefficients for formula (1) have to be obtained by interpolation; the first-order spline interpolation was used to generate those coefficients for the calculations described in this paper.

Secondly it has been discovered that program's output depends on the filter-splitting method. Different calculation results can be obtained for both *HVL* and correction factors by changing the maximum filter thickness and the number of steps. The project described in this paper attempted to optimize calculation results by varying the filter thickness. It was found that the maximum filter thickness of 5 *HVL*1 (according to the ISO4037-1:2019) split into 50 steps is a reasonable choice with respect to both the output discrepancy and the calculation time.

Finally the result produced by a simulation utilizing the presented method depends on the choice of the interpolation function for the dependence $I = f(h)$ (Figure 2). Interpolating with the sum of three decaying exponentials suggested in [2] seemed to be a good choice when the deposited energy was used as the IC response, but that interpolation technique has proved to be poor when using air kerma. The cubic spline interpolation was utilized for the air kerma calculations described in this paper. The choice of such an interpolation technique can very well be the reason for inflection points appearing in the resulting interpolated curve.

All these flaws can lead to discrepancies between the calculated and the ISO-tabulated *HVL* values regardless to the modelling error. This can also lead to discrepancies in the output results between the two methods, the one using deposited energy as the IC response and the presented one using air kerma, for the *HVL* and for correction factors.

It should be noted here that the contribution of scattered photon radiation to the IC response is always positive and leads to overestimation of *HVL* when directly measured. Considering this fact as well as the magnitude of the discrepancy caused by scattered photon radiation, it can be argued that the use of the correction factors obtained in this paper brings the result of direct *HVL* measurements closer to their experimental values.

## Conclusion

The developed method allows taking into account the contribution of radiation scattered on the filter when determining the *HVL* of the photon radiation field generated by the X-ray unit. Its practical implementation was carried out in the FLUKA Monte Carlo program. The simulation showed that the contribution of the scattered radiation to the calculated *HVL* value does not exceed 5 % of its true meaning for X-ray radiation fields with the tube voltage under 300 kV.

It was found that the contribution of scattered radiation to the ionization chamber readings is a positive value. That in turn leads to overestimation of the *HVL* calculation result in direct measurements. This overestimation was mitigated by means of correction coefficients.

The main difference between the method proposed in this study and the analogues is the choice of the calculated value. The use of air kerma as a value of the model response to the influence of photon radiation made it possible to reduce the calculation time. In particular, the time spent on the calculation of the correction coefficients for the *H*-quality series was reduced by 16 times, for the *L*-quality series by 8 times, and for the *N*-quality series by 6 times (as compared to the standard method of calculation). This made it possible to calculate correction coefficients for the "source-detector" distance equal to 2.5 m (according to ISO4037-1:2019 requirements) for these quality series. Based on the analysis of similar scientific papers, we can assume that this result has never been published.

Due to its calculation speed the method proposed in this paper can be implemented on an ordinary workstation. This make it possible to extend its application to a wide range of users of X-ray equipment. Which in turn can contribute to a wider implementation of ISO 4037-1:2019.

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