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SCATTERING FRACTION OF X-RAYS INCIDENT ON A PHANTOM FROM THE MEASURED ENERGY SPECTRA

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ABSTRACT

The scattering fraction of X-rays incident on a polymethil–methacrylate/aluminum phantom have been calculated from the measured spectra of the primary and scattered radiation in different directions. Constant potential X-ray equipment has been utilized to produce beams with a maximum energy in the range 40-90 keV. The energy spectra have been measured by means of an Amptek XR-100CR system with a silicon PIN photodiode detector. The raw spectra have been corrected for the dependence of the detector efficiency on the photon energy, and utilized to determine the ambient dose equivalent (ADE) due to the primary beams and to the radiation scattered at the angles 30º, 90º and 150º with the incident beam direction. The spectra have been calibrated in kerma units by means of the data obtained simultaneously with an ionization chamber. For the determination of the ADE, the kerma spectra (grays) was converted to sievert units through the energy dependent factors published in the ICRU 57 report. Scattering fractions were determined as the ratio of these two ADE values, according to the 453 Brazilian Health Ministry Rule. Results show that the obtained angular dependence of the scattering fractions follows the same behavior of previous measurements recently published.

Keywords: X-ray spectrometry, scattering fraction, ambient dose equivalent, PIN photodiodes, radio diagnostic.

I. INTRODUCTION

The fraction of the incident radiation scattered off the patient is an important parameter for the calculation of radiation protection barriers. For this purpose, in agreement with 453 Brazilian Health Ministry Rule[1], the scattering fraction may be defined as the ratio of the ambient dose equivalent (ADE) due to the scattered radiation, at 1m from the center of the scattering object (patient, phantom), to the ADE due to an incident primary beam of known area, at 1m from the X-ray tube.

The ICRU Report 57[2] states that the ambient dose equivalent, *H*(d)*, in Sv units, is the appropriate operational quantity for the area monitoring, defined as the "dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth *d* on the radius opposing the direction of the aligned field", with the recommendation that *d* be 10 mm for penetrating radiations and 0.07 mm for low-penetrating radiations.

A few works refer to the practical form to determine *H*(d)*[3], but it's clear that its value depends on the way we link physical quantities, like air kerma K_a , in *Gy* units, to the operational quantity *H*(d)*. Most common commercial radiation monitors, working coupled to ionization chambers, have built-in conversion factors fixing that

1 R = 0.00873 Gy = 0.010 Sv, i.e.,

1 Gy = 1.145 Sv (1)

See, for example, Ref. 4 [4]. Moreover, national regulations, like 453 Ministerial Rule (1998)[1], adopt ambient dose equivalent to verify the conformance with dose constraint levels in area monitoring and also fix the conversion factor 1.14 Sv/Gy.

On the other hand, ICRU Report 57, in agreement with ICRU Report 47[5], presents tables of the conversion factor $H^*(d) / K_a$ (Sv/Gy) as a function of photon energies, based on data from Wagner *et al.*[6] and Grosswendt *et al.*[7], and recommends that "the mean or effective conversion coefficients for broad spectra must be determined by integration over the entire radiation energy spectrum".

In a previous work[8] it has been showed that, for mammography units, whose involved energies are too low (up to 35 keV), the adopted fixed value is unreal and produces overestimated final results for $H^*(d)$. Knowledge of the radiation beam spectral distribution permits the conversion between units taking into account the $H^*(d) / K_a$ energy distribution curve[1].

In the present work, spectra of radiology beams incident on a patient equivalent phantom and of the corresponding beams scattered at some angles were measured with a PIN photodiode and values of ambient dose equivalent were calculated trough them, utilizing the constant conversion factor 1.14 Sv/Gy as well as the curve of $H^*(d) / K_a$ *vs.* photon energy. From these values, the corresponding scattering fractions were determined according to the 453 Ministerial Rule.

II. MATERIALS AND METHODS

Utilized equipment. Measurements have been carried out in the facilities of the Radiation Physics Laboratory, IEE, at the University of São Paulo, São Paulo, in a shielded room. X-ray beams were emitted by a constant potential Philips MGC 40 apparatus, with tungsten target tube and a fixed additional filter of 3.0 mm Al. Primary beams have been scattered by a Nuclear Associates patient equivalent phantom, made by a set of six 2.5 cm thick polymethil–methacrylate slabs with two Al plates, one 1.25 mm thick sandwiched between the first and second slabs and the other, 2.0 mm thick, between the fifth and the sixtieth PMMA plates. This phantom has been set up with its center placed 1 meter away from the X-ray tube focal spot, and the primary (incident) radiation field was 400cm^2 on the surface of the phantom. The scattering measurements have been made at 30, 90 and 150 degrees from the incident beam direction. Tube potentials from 40 to 90 kVp, in steps of 10 kVp, and different currents and exposure times have been selected for the measurements; these same kVp values have been set in the measurements of the primary beams.

The beams scattered at these angles were detected by a Radcal 180 cm^3 ionization chamber (Radcal Corporation) and a portable high resolution Amptek XR100CR spectrometer (Amptek, Inc.), made with a silicon PIN photodiode cooled by Peltier cells. For primary radiation detection, a 6 cm^3 ionization chamber and the spectrometer have been set 4.24 m distant from the tube focal spot; for the scattering measurements, the distance between the center of the phantom and both detectors have been always 1 m. Current have been made low enough to avoid pulse pile-up and excessive dead time losses in the spectrometer. The resulting pulse height distributions have been analyzed by a multichannel analyzer and the raw energy spectra was obtained for each set of measurements.

As the walls shielding scatter meaningful quantities of radiation and there are leakage radiation through the tube involucre, a measurement of the radiation background has been made after every single measurement of both primary and scattered beams. For this purpose, a radiation stopper, made with 16 mm Pb and 1.3 mm Cu, has been set in front of the detectors to block the primary beam as well as the beam scattered by the phantom at every angle. The distance from the stopper to the detectors has been determined using an AutoCAD draw (Autodesk, Inc.), which has reproduced the geometry of each measurement. After the doses and spectra measurements, each background has been subtracted from the correspondent measurement.

Spectra of the X - and γ - rays emitted by radioactive sources of ^{241}Am, ^{133}Ba and ^{109}Cd (AEA Technology) have been measured in the same experimental sessions, for the calibration of the spectrometer. High enough counting statistics were obtained, and gauss curves were fitted to each recognized peak, in order to construct an energy *vs.* channel curve, using published energy and intensity data[9].

Spectra Stripping Procedure. The raw spectra have been corrected for the change of detector efficiency with photon energy. As the detector depletion layer thickness is very thin (≤ 300 μm), the entire photon energy are deposited only by photoelectric processes, and partial deposition occurs by single Compton scattering. On the other hand, a few photoelectrons escape from the *i* layer of the photodiode, producing pulses of incomplete charge collection. Finally, photons that pass through the depletion layer can produce fluorescence radiation on the back metallic contact, which can affect the resultant spectrum.

As the pulse height distribution involves all of these effects, it must be corrected if one wishes to obtain the true energy spectrum of the scattered beam reaching the detector. Therefore, if the depletion layer thickness can be estimated, it is possible to make a theoretical approach to determine the dependence of the intrinsic *full energy efficiency* h with the photon energy, taking into account the photoelectric efficiency, compensating for the escape of the photoelectrons and discarding the influences of the counts due to Compton and fluorescent radiation in the detector[10].

In the present work, we have preferred to determine experimentally the *overall efficiency* h_e , through the radiation spectra of calibration sources made in the same geometric conditions, statistics, amplifier gain and so on. With the Amptek detector it is more difficult to determine theoretically the value of h, as the actual depletion thickness is very poorly known, because of the Rise Time Discriminator (RTD) circuit of the system which rejects amplified pulses with long rise time, in order to enhance the energy resolution, so counting only the events occurring near the entrance surface[11].

Fig. 1 shows the graph of determined values of *overall efficiency vs.* photon energy. In the same figure, it is possible to see the theoretical curve of silicon *intrinsic full energy efficiency* calculated for the nominal 300 μm and for

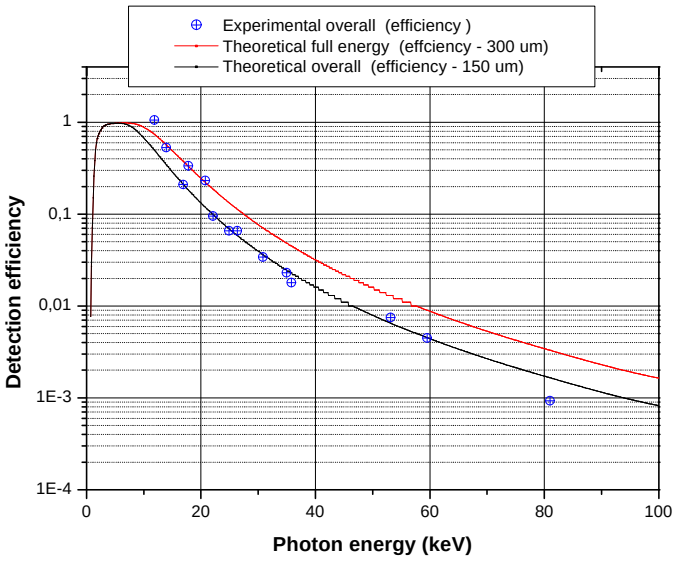

Figure 1. XR100CR full energy efficiency *vs.* photon energy. Points represent overall efficiency experimentally determined as described in the text. Red and green lines represent theoretical intrinsic efficiency calculated, respectively, for 300 and 150 μm depletion thickness.

the 150 μm depletion thickness. We can observe that the XR100CR with the RTD on acts roughly like a 150 μm depletion layer detector, in this case.

So, for correcting the raw spectra, both for radioactive sources and X-ray tubes, after energy calibration and subtraction of incomplete charge and Compton counts, the *true* spectra (number of photons *vs.* energy) can be obtained by

$$N_t(E) = N_m(E) / (h_e(E) \cdot f_w(E)) \qquad (1)$$

where, for the energy E, $N_m(E)$ is the measured spectrum and $f_w(E)$ is the attenuation factor for the detector window material (beryllium) .

Determination of the Ambient Dose Equivalent. After the correction of the measured spectra for the change of the efficiency with energy, the *air kerma* spectra can be determined, in order to calculate the ambient dose equivalent $H^*(d)$ for the analyzed installation.

Firstly we must convert the corrected spectra to *fluence* units (photons / keV.m^2), using the detector (or the collimator) area. After, it is possible to determine the air kerma spectra (in μGy / mAs) by using the air energy transfer coefficient and the total utilized *mAs* product. It was made for each measured and corrected spectra.

The *ambient dose equivalent* (in mSv / week) for that installation and measurements, both for primary and secondary radiation, considering the scattering at 30 ^{o}, 90^o and 150 ^{o}, have been obtained by two ways: first, using the constant conversion factor 1.14 Sv/Gy[1,4]; second, through the $H^*(10) / K_a$ *vs.* photon energy curve, showed in Figure 2.

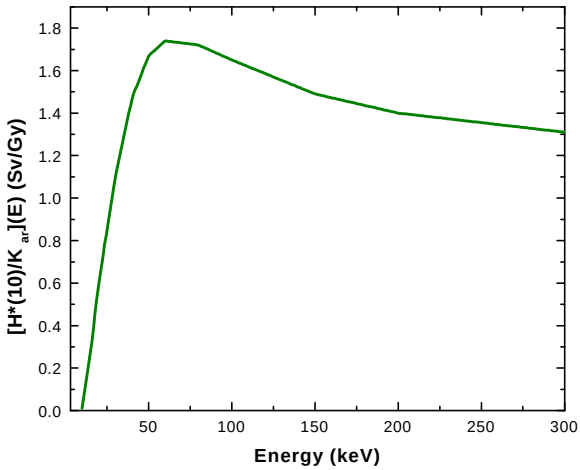

Figure 2. Conversion factor $H^*(10) / K_a$ *vs.* photon energy (see text), like in Refs. [2] and [5]

Determination of the Scattering Fractions. For both the situations, the scattering fraction values have been calculated from the ratio of the ambient dose equivalent for the scattered radiation beam to that of the incident radiation[1]. These calculations have been performed considering the conversion factor $H^*(10) / K_a$ being fixed as well as varying with photon energy, for all the measured scattering angles and set tube voltages, both to the primary and the scattered radiation.

III. RESULTS

Tables 1 and 2 show samples of the preliminary values of the scattering fractions obtained through the methodology described above, considering the conversion factor $H^*(10) / K_a$ respectively fixed or energy dependent.

Table 3 shows results of attempts to evaluate a fixed value for the above conversion factor adequate for each measurement configuration.

Fig. 3 shows, as an example, the corrected spectra, in μGy/mAs.keV obtained from the measurements made with the 80 kV.

Table 1. Values of the fraction of radiation scattered by the phantom, 1 meter from its center, per cm^2 of the incident area on the phantom, at some angles, for each kVp applied to the tube, adopting a fixed value for the Sv/Gy conversion factor.

kVp (kV)	Scattering angles		
	30°	90°	150°
40	$2.29.10^{-6}$	$1.29.10^{-6}$	$2.34.10^{-6}$
50	$2.49.10^{-6}$	$1.55.10^{-6}$	$2.82.10^{-6}$
60	$2.50.10^{-6}$	$2.26.10^{-6}$	$3.20.10^{-6}$
70	$2.48.10^{-6}$	$2.38.10^{-6}$	$2.55.10^{-6}$
80	$2.70.10^{-6}$	$2.65.10^{-6}$	$3.15.10^{-6}$
90	$2.88.10^{-6}$	$2.60.10^{-6}$	$2.63.10^{-6}$

Table 2. Values of the fraction of radiation scattered by the phantom, 1 meter from its center, per cm^2 of the incident area on the phantom, at some angles, for each kVp applied to the tube, taking into account the energy dependence of the Sv/Gy conversion factor.

kVp (kV)	Scattering angles		
	30°	90°	150°
40	$2.19.10^{-6}$	$1.23.10^{-6}$	$2.07.10^{-6}$
50	$2.35.10^{-6}$	$1.50.10^{-6}$	$2.52.10^{-6}$
60	$2.30.10^{-6}$	$2,26.10^{-6}$	$2.90.10^{-6}$
70	$2,18.10^{-6}$	$2,33.10^{-6}$	$2.34.10^{-6}$
80	$2.60.10^{-6}$	$2.55.10^{-6}$	$2.90.10^{-6}$
90	$2.75.10^{-6}$	$2.50.10^{-6}$	$2.41.10^{-6}$

Table 3. Determined fixed values of Sv/Gy conversion factor to be utilized for each scattering angle and kVp applied to the tube, both for primary and the scattered beams, taking into account the energy dependent calculations.

kVp (kV)	Primary	Scattering angles		
		30°	90°	150°
40	1.070	1.021	1.034	0.948
50	1.218	1.151	1.175	1.088
60	1.307	1.201	1.330	1.182
70	1.364	1.312	1.333	1.265
80	1.438	1.377	1.386	1.321
90	1.483	[illegible]	[illegible]	1.361

IV. DISCUSSION

In Table 3 we can observe that, despite the recommendation of 453 Brazilian Health Ministry Rule[1], results show that it would be better to adopt the Sv/Gy conversion factor energy dependent values[2] or a fixed value for each kVp utilized in the measurements, in order to not under or overestimate measured dose values. As we can see, differences between these values and the recommended 1.145 Sv/Gy factor varies from - 17 % to + 29 %, in the range of kVp utilized.

Results also show that the obtained angular dependence and the order of magnitude of the scattering fractions agree with the data previously published[12,13]. Obtained values are strongly dependent of the stability of ionization chamber and monitor, as well as of the accuracy and reproducibility of the geometry of tube-phantom-detector array.

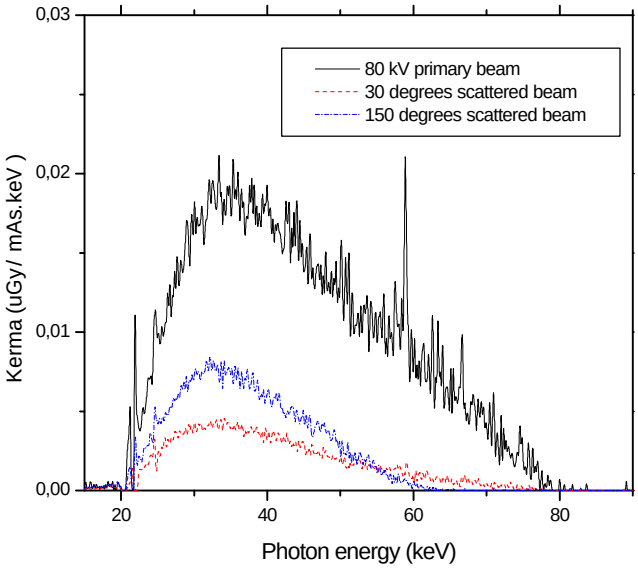

Figure 3. Spectra of primary beam as well as of 30 degrees and 150 degrees scattered beams, in kerma units, after the correction procedure (see text), for 80 kV tube peak potential.

AKNOWLEDGEMENTS

The authors wish to thank to FAPESP Brazilian agency for the partial support to this work.

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