Comparison in determination of mass-energy transfer coefficients

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Abstract. The values obtained through definitions, specific software and measurements of the mass energy transfer coefficients referring to X-ray beams in air using the range of 30 to 150 kV. They allowed the spectra and calculated evaluation the respective mass coefficients. The results shown a decreasing behavior with energy, ranging from 0.3733 to 0.0439 cm²/g, differing from the behavior of monoenergetic beams above 100 keV.

1. Introduction

The entrance surface air kerma and incident air kerma are quantities derived from the air kerma quantity [1]. These quantities are used to verify the given doses in radiodiagnostic practices and compare with reference levels in quality assurance programs implementations. These doses and the equipment performance have great relation too. Following this way, the determination of mass energy transfer coefficients for X-ray spectra to voltage range from 30 to 150 kVp is fundamental.

Researchers and collaborators in quality assurance programs use the mass energy transfer coefficients of the tables present in Attix, being the only reference, but the Attix values come from monoenergetic sources. X-rays are formed by spectra with energies of zero to the maximum beam energy for each selected voltage. It can then be concluded that there must be some discrepancy between the coefficients for monoenergetic and spectral sources.

X-ray diffraction coefficients for multi-energy sources were not considered by Attix [2], that used only mono-energy sources as reference to obtain the coefficients and water-air coefficient ratios for X-rays [3, 4].

Therefore the determination of mass transfer coefficients using X-ray spectra has great relevance because nowadays some systems do not use the ionization chamber as a detector. Solid-state detectors like diodes and specific crystals were introduced as dosimetric sets. These solid-state detectors can be calibrated through the energy fluence once the kerma can be considered a function of the energy fluence and energy mass transfer coefficient, for each energy or voltage [2].
2. Materials and Methods

2.1 Spectrum Processor
The Spectrum Processor [4,5] is a software, template are shown in figure 1, capable of generate X-ray spectra, providing photon fluence (photons / mAs mm$^2$) with 0.5 keV intervals, from physical information pre-archived in the matrix, ranging from zero to the maximum beam energy. In addition to the spectrum for each voltage, the program also provides the air kerma at 750 mm from the focal point per kVp selected.

![Figure 1. A) Software communication Interface; B) Example of generated spectrum with 60 kVp, anodic angulation of 18°, total filtration of 3.1 mmAl and 5% of Ripple voltage.](image)

The program was developed by the Institute of Physics and Engineering in Medicine – IPEM [4,5]. The Software interface allows you to enter data such as kVp, total filtering, anode angle, ripple Voltage and target material. Allows generated spectrum to be save in other formats, in order to export the file to spreadsheets. The use of the program requires a 16 or 32 bit operating system and set to British configurations.

2.2 Mass Energy Transfer Coefficients
Almost thirteen spectra from 30 up to 150 kVp were generate in the Spectrum Processor software, with 10 kVp intervals. The air kerma correspondents were obtained for each nominal voltage. The focal point distance to the measurement point was established as 1000 mm, like clinic practices, by the distance square inverse law, once the standard distance in the Spectrum Processor software is 750 mm. Was established in 2.5 mmAl additional filtration and 20° of anodic angulation at the simulation.

The generated photons fluence for each energy spectra were exported to a spreadsheet and processed. The treatment consisted in calculate the energy fluency for each spectra related and voltage. Once all the energy fluence were calculated to each tube voltage, with equation 1.

$$\psi_E = \int E \phi_E$$  (1)
The coefficients for each tube voltage, from 30 to 150 kVp, were calculated through equation 2 using the air kerma obtained with Spectrum Processor software and the total energy fluency by each voltage, equation 1.

$$K = \int_{F_{\text{air}}}^{F_{\text{0}}} \psi \left( \frac{\mu}{\rho} \right)_{e,z} \, dz$$

(2)

The maximum energy peaks were observed for each nominal voltage because the effective X ray energy beam does not mean the same voltage applied.

The coefficients were compared with the Attix [2] monoenergetic data and Oliveira interpolated data [2,4,6].

3. Results

The generated mass energy transfer coefficients are shown in figure 2 as function of the beam's main energy and the nominal voltage. The comparison between the Attix data [2], Oliveira [6] and Teixeira [4] are shown in table 1. The difference between the values demonstrates that ionizing sources used at each methodology are fundamentals to obtain these mass energy transfer coefficients to air used by diagnostic X ray.

4. Discussion

The coefficients obtained behave in a decreasing way as higher is the tube voltage. This phenomenon is due to the fact that when the average energy of the beam is higher the dose deposition will be lower at the same point in the air, since the kerma is directly proportional to the coefficient.

This would also be repeated for materials with other densities, so when the energy is increased the dose deposition decreases at the measurement point but increases at locations beyond the initial measurement point.

Data Attix [2] doesn’t show the coefficients related to 70, 90, 110, 120, 130 and 140 keV to monoenergetic beams. Therefore the linear interpolation [6] had to perform to obtain the coefficients related to these energies.

It should be noted that the main Oliveira's objective [6] was to verify the applicability of NaI (TI) Scintillation detectors of work was to verify the applicability of NaI (TI) in air kerma measurements for diagnostic X ray beams and these results were acceptable considering the coefficients lack of multi-energy spectra at the literature, showing the relevance of continue study of these coefficients.

Table 1 shows the coefficients obtained by simulation, data Attix and linear interpolation [2,4,6]. The firsts’ data shows the nominal voltage and the second the effective energy related. The effective energy is considered as the most intensity energy in the spectra to each voltage. The last column presents each one monoenergetic nominal beams from data Attix [2] and linear interpolation [6].

Data Attix also shows a behaviour decreasing at higher beam energy, but for 150 keV beam the coefficient shows a 0.0016 cm$^2$/g increase in relation to 100 keV beam, table 1, that this phenomenon is contrary to the X ray behaviour.
This could be understood due to the possible contribution of the radiative kerma component ($K_r$). In conventional X ray beams the maximum energy occurs with very low intensity, whereas for a monoenergetic beam, one hundred percent of the photons are obviously as the same energy.

However, the consequence will be that the Compton scattering probability increases to energies greater than 100 keV as a function of the material atomic number, the air in this case.

Table 1. Comparison between the values found in Attix [2]/Oliveira [5] and Teixeira [4].

| Voltage (kV) | Effective energy (keV) | $\mu_e/\rho$ (cm$^2$/g) $^*$ | Monoenergetic Beam (keV) |
|--------------|------------------------|-------------------------------|-------------------------|
| 30           | 23.1                   | 0.3733                        | 30                      |
| 40           | 27.8                   | 0.2233                        | 40                      |
| 50           | 31.8                   | 0.1575                        | 50                      |
| 60           | 35.4                   | 0.1219                        | 60                      |
| 70           | 38.7                   | 0.0997 $^*$0.0274             | 70                      |
| 80           | 42.2                   | 0.0833                        | 80                      |
| 90           | 45.4                   | 0.0717 $^*$0.0238             | 90                      |
| 100          | 48.3                   | 0.0636                        | 100                     |
| 110          | 51.0                   | 0.0575 $^*$0.0237             | 110                     |
| 120          | 53.5                   | 0.0529 $^*$0.0240             | 120                     |
| 130          | 55.8                   | 0.0493 $^*$0.0244             | 130                     |
| 140          | 58.1                   | 0.0463 $^*$0.0247             | 140                     |
| 150          | 60.3                   | 0.0439                        | 150                     |

* mass energy transfer coefficients obtained by Attix[2] values linear interpolation.

The linear interpolations [6], table 1, shows the same decreasing behavior for 70 and 90 keV, but between 110 and 140 keV, the above mentioned increasing behavior is repeated again, thus bringing about a greater results reliability in the of linear interpolations performed.

Peixoto and Andreo [3] compared the air-water ratios of the mass energy absorption coefficients of some works in the range of 10 to 160 kV. The decreasing behavior and subsequent increase can also be observed, but the increase starts to occur from Half Value Layer - HVL at 2 mmAl, that is, 70 kV approximately, according to the protocols analyzed.

When observe data Attix [2] and linear interpolation [6], the increment probability happens from approximately 100 keV, but in Peixoto and Andreo [3] this behavior is anticipated. This phenomenon was attributed to insertion of the water in the relation, because in this mid the Kerma component of collision ($K_c$) increases, due to the increased density of one of the materials involved in the measurement.

5. Conclusions
The coefficients generated behave were expected for a radiodiagnostic X ray beam, but presented a decreasing behavior in its values with the voltage increase. For the monoenergetic beams used as reference [2,6], must have criterion in the insertion of these coefficients, because in this way, other effects for a same measurement point may be probable, take into account the uncertainty increasing of
the result and obviously the exact measurement point, due to a non-focal dose deposition for energy ranges greater than 100 keV.

Another discovery found is data Attix were the present’s values of the mass energy-transfer coefficients and to the mass energy-absorption coefficients to 100 and 150 keV beams were the same. Mass energy transfer coefficients by monoenergetic beams cannot be considered as equal to mass energy absorption coefficients due to secondary electrons and "nonlocal" energy deposition for "higher" energy levels (≥ 100 keV). So these coefficients from monoenergetic beams also cannot be used at kerma in X ray diagnostic simulations measurements.

Appropriate calibration is recommended for chambers or other dosimetric systems of clinical use in diagnostic X ray beams with energies grater than 90 keV and/or voltage greater than 90 kV. It is necessary the correct layer buildup modeling, in order to obtain the desired electronic equilibrium.

References

[1] IAEA 2007 Technical Reports Series 457 - Dosimetry in diagnostic radiology: An international code of practice. Vienna. p 372.
[2] Attix F H 1986 Introduction to Radiological Physics and Radiation Dosimetry. John Wiley & Sons (New York, Wiley-Interscience). p 607.
[3] Peixoto J G and Andreo P 2000 Determination of absorbed dose to water in reference conditions for radiotherapy kilovoltage x-rays between 10 and 300 kV: a comparison of the data in the IAEA, IPEMB, DIN and NCS dosimetry protocols.” Phys. Med. Biol., vol. 45, no. 3, pp. 563–575.
[4] Teixeira G J 2013 Coeficientes de Transferência de Energia em Massa para Raios X Diagnóstico: Determinação e Análise. Instituto de Radioproteção e Dosimetria. Rio de Janeiro. p 79.
[5] IPEM 1997 Spectrum Processor Software. UK.
[6] Oliveira L S R 2011 “Avaliação da resposta de detetores cintiladores de NaI(Tl) em medição de kerma no ar em feixes de raios x diagnóstico. Instituto de Radioproteção e Dosimetria. Rio de Janeiro.