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Calculation of the humidity correction factor in air kerma strength measurement for ^{125}I and ^{103}Pd brachytherapy sources and its uncertainty by Monte Carlo method

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ABSTRACT

Humidity is one of the sources of systematic error in the absolute measurement of air kerma strength of ^{125}I and ^{103}Pd low energy brachytherapy sources by using free air ionization chambers. In this paper, the humidity correction factor and its uncertainty for several environmental conditions have been calculated by applying an indigenous developed uncertainty analysis algorithm programmed in FORTRAN. The results of the analysis showed that the humidity could affect the corrected measured source strength value by about 0.2%.

1. Introduction

Nowadays low energy brachytherapy sources, such as ^{125}I and ^{103}Pd are used extensively for treatment of various kinds of cancers like eye, head, neck, breast, cervix and especially prostate cancers (Dennis, 2000; Meigooni et al., 2004; Bernard, Vynckier, 2005). For the application of these sources, accurate determination of their strength is one of the most important issues for radiotherapeutic treatment.

In 1988, the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM) formed a task group to assimilating information of brachytherapy sources. The report of this task group (AAPM TG43) established the air kerma strength "S_K" as the recommended metric for the source strength of these sources (Rivard et al., 2004).

Air kerma strength, S_K, as given in Eq. (1) (Rivard et al., 2004; Nath et al., 1995), is defined as the air kerma rate $\dot{K}_\delta(d)$, in vacuo due to photons of energy greater than the cut off value "δ" at distance d, multiplied by the square of this distance "d^2"

$$S_K = \dot{K}_\delta(d) \cdot d^2 \tag{1}$$

The energy cut off, δ, is intended to exclude very low energy or contaminant photons (for example characteristic X-rays originating in the outer layers of the source titanium cladding) that increase $\dot{K}_\delta(d)$ without contributing significantly to dose at distances greater than 0.1 cm in tissue. The value of δ is typically 5 keV for low energy photons emitted by brachytherapy sources, and is dependent on the application (Rivard et al., 2004).

The strength of low energy brachytherapy sources, ^{125}I and ^{103}Pd, is measured by standard free air ionization chambers, in primary standard dosimetry laboratories. At present, three systems of parallel plate free air ionization chambers have been constructed for the absolute measurement of air kerma strength in low energy brachytherapy sources (Seltzer et al., 2003; Selbach et al., 2008; Culberson et al., 2006). In this regard, Nuclear Science and Technology Research Institute in Iran recently, has designed and constructed a parallel plate free air ionization chamber for absolute measurement of air kerma strength of ^{125}I and ^{103}Pd low energy brachytherapy sources. This free air ionization chamber has movable electrodes and different size of apertures, so measurements can be done in different volumes. The maximum and minimum of collecting volume are 5089 cm^3 and 508 cm^3 respectively.

For absolute measurement of air kerma strength by this chamber, several correction factors should be calculated to take into account the systematic effects of various factors. One of the sources of these systematic errors is the effect of humidity. In this research the humidity correction factor is calculated for various relative

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humidity values including its uncertainty by applying an indigenous Monte Carlo analysis algorithm programmed in FORTRAN.

2. Materials and methods

Air kerma is the sum of initial kinetic energies of all charged particles liberated by uncharged particles per unit mass of air (ICRU Report 60, 1998). Air kerma rate can be calculated by the following equation:

$$\dot{K}_{air} = \sum_i \dot{\phi}_{E_i} E_i \left(\frac{\mu_{tr}}{\rho}\right)_{E_i} \tag{2}$$

where $\dot{\phi}_{E_i}$ is the photon fluence rate at energy E_i and $(\frac{\mu_{tr}}{\rho})_{E_i}$ is the mass energy transfer coefficient at energy E_i.

As recommended by the AAPM, the strength of brachytherapy sources should be calculated in terms of the air kerma strength. The results of a free air ionization chamber measurement of low energy photons are then determined according to the following equation (Seltzer et al., 2003):

$$S_K = \left(\frac{W}{e}\right)_{air} \frac{I_{net} d^2}{\rho_{air} V_{eff}(1-\bar{g})} \prod_i k_i \tag{3}$$

where W/e is the mean energy required to produce an ion pair in air, I_{net} is the measured net ion current (current minus background and leakage), d is the source-to-aperture distance, ρ_{air} is the density of air, V_{eff} is the product of the aperture area and the length of the collecting volume, g is the fraction of the initial electron energy lost by bremsstrahlung production in air, for low energy photons (<40 keV) emitted by ^{125}I and ^{103}Pd seeds, g is very small (<0.00065) which is neglected and k_i is the correction factor due to the effects of air attenuation, scattering of photons, recombination, humidity, etc. (Kashian et al., 2011; Burns and Büermann, 2009; Burns and Kessler, 2009; Grimbergen et al., 1998; Lee et al., 2005; Lin and Chu, 2006).

The net ionization current "I_{net}" is given by the following equation:

$$I_{net} = \frac{\dot{K}\rho_{air} V_{eff}}{(\frac{W}{e})_{air}} \tag{4}$$

This equation is used for determination of net current in air. Humidity affects the results of the free air chamber measurements in a number of ways including, photon mass energy transfer coefficient, air density and the mean energy required to produce an ion pair in air. For the combined effects of these changes, a humidity correction factor "k$_{humidity}$" can be calculated by the following equation:

$$k_{humidity} = \frac{I_{net}(in\ dry\ air)}{I_{net}(in\ humid\ air)} = \left(\frac{\rho_D}{\rho_H}\right)\left(\frac{W_H}{W_D}\right)\left(\frac{\sum_j \phi_{E_j} E_j \left(\frac{\mu_{tr}}{\rho}\right)_{E_{j_D}}}{\sum_j \phi_{E_j} E_j \left(\frac{\mu_{tr}}{\rho}\right)_{E_{j_H}}}\right) \tag{5}$$

where ρ is the air density, W is the mean energy expended in air per ion pair formed when the initial kinetic energy of a charged particle is completely dissipated in air and $(\frac{\mu_{tr}}{\rho})_{E_i}$ is the mass energy transfer coefficient at energy E_i. The indices "D" and "H" indicate the parameters for dry and humid air respectively.

The density of humid air "ρ_H" was evaluated by equation of Giacomo (1982), in which the density of moist air can be obtained from thermodynamical temperature, atmospherical pressure and the humidity of air as given in the following equation (Giacomo, 1982).

$$\rho_{air} = \frac{P}{ZRT}\left(\sum_i x_i M_i / x_i\right)\left[1 - x_v\left(1 - M_v / \left(\sum_i x_i M_i / x_i\right)\right)\right] \tag{6}$$

where P is the air pressure, M_i is the molar mass of various constituents of the dry air, x_i is their molar fraction, M_v is the molar mass of water vapor, x_v is the mole fraction of water vapor, Z is the compressibility factor, R is the molar gas constant and T is the termodynamical temperature in kelvin.

Elements and compounds in the dry air with their mole fractions are given in Table 1.

The mole fraction x_v is determined by the following equation (Giacomo, 1982):

$$\begin{aligned} x_v = {} & \frac{h}{p}\left(1.00062 + 3.14 \times 10^{-8} P + 5.6 \times 10^{-7} t^2\right) \\ & \cdot \exp(1.2811805 \times 10^{-5} T^2 - 1.9509874 \times 10^{-2} T \\ & + 34.04926034 - \frac{6.3536311 \times 10^3}{T}) \end{aligned} \tag{7}$$

where h is the relative humidity, t is the temperature in °C, T is the temperature in kelvin and P is the pressure expressed in pascal.

By determination of mole fraction of water vapor in moist air, mass energy transfer coefficient can be calculated by the following equation:

$$\left(\frac{\mu_{tr}}{\rho}\right)_H = \frac{(1-x_v)(\sum_i x_i M_i / x_i)}{M}\left(\frac{\mu_{tr}}{\rho}\right)_D + \frac{x_v M_v}{M}\left(\frac{\mu_{tr}}{\rho}\right)_{water} \tag{8}$$

where $(\frac{\mu_{tr}}{\rho})_{water}$ is the mass energy transfer coefficient of water and $M = (1-x_v)(\sum_i x_i M_i / x_i) + x_v M_v$ with other parameters as defined before.

The variation of W_H/W_D as a function of the partial pressure of water vapor is shown in Fig. 1 (Seltzer, 1993). The partial pressure of water vapor is equal to the mole fraction of water vapor in moist air. Niatel's data has been used in this paper, by fitting a curve.The uncertainty in the correction factor has been calculated by a developed Monte Carlo uncertainty analysis algorithm written in FORTRAN. In this program, a normal distribution has been attributed to each of the uncertain parameters of Eq. (5). Humidity correction factor is calculated for each set of randomly sampled values of various uncertain parameters. The correction factor has been calculated for several set of sampled values, and finally a distribution has been obtained for the correction factor, giving the mean, standard deviation and standard deviation of the standard deviation. The mean is the humidity correction factor and the standard deviation is its uncertainty. The relative standard deviation for various parameters are considered to be 2%, 2%, 0.1%, 0.1%, 0.1% and 0.1% for mass energy transfer coefficient in air "$(\mu_{tr}/\rho)_{air}$", mass energy transfer coefficient in water "$(\mu_{tr}/\rho)_{water}$", temperature "T", pressure "P", relative humidity "h" and the ratio of the mean energy required to produce an ion pair for humid air to dry air "$(\frac{W_H}{W_D})$", respectively.

This program has been divided in the following sections:

Table 1
Composition of dry air (Giacomo, 1982).

Components	Molar mass (in 10^{-3} kg/mol)	Mole fraction (%)
N_2	28.0134	78.101
O_2	31.9988	20.939
Ar	39.948	0.917
Co_2	44.010	0.040
Ne	20.18	18.2×10^{-4}
He	4.0	5.2×10^{-4}
CH_4	16.0	1.5×10^{-4}
Kr	83.8	1.1×10^{-4}
H_2	2	0.5×10^{-4}
N_2O	44	0.3×10^{-4}
CO	28	0.2×10^{-4}
Xe	131	0.1×10^{-4}