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Technical note

Polarity and ion recombination corrections in continuous and pulsed beams for ionization chambers with high Z chamber walls

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ABSTRACT

In this work, the response of Farmer-type ionization chambers fitted with high atomic number (Z) walls is studied, and results of the effects of such walls on polarity and ion recombination correction factors in both continuous and pulsed beams are presented.

Measurements were made in a continuous Co-60 beam and a pulsed 6 MV linac beam using an Exradin-A12 ionization chamber fitted with the manufacturer's C-552 plastic wall, as well as geometrically identical walls made from aluminum, copper and molybdenum. The bias voltage was changed between 10 values (range: +50 to +560 V). Ion recombination was determined from Jaffé plots and by using the "two-voltage technique". The saturation charge measured with each chamber wall was extrapolated from Jaffé plots. Additionally, the effect of different wall materials on chamber response was studied using MCNP simulations.

Results showed that the polarity correction factor is not significantly affected by changes in chamber wall material (within 0.1%). Furthermore, although the saturation charges greatly vary with each chamber wall material, and charge multiplication increases for higher atomic number wall materials, the standard methods of calculating ion recombination yielded results that differed by only 0.2%. Therefore, polarity and ion recombination correction factors are not greatly affected by the chamber wall material. The experimental saturation charges for all the different wall materials agreed well within the uncertainty with MCNP simulations. The breakdown of the linear relationship in Jaffé plots that was previously reported to exist for conventional chamber walls was also observed with the different wall materials.

1. Introduction

In radiation therapy, beam quality has been studied for either its physical and dosimetric relevance, or its relevance and relation to radiobiological damage; indeed, beam quality has been quantified in several different terms depending on application. We attempt to develop a technique to measure the beam quality of radiation beams by measuring linear energy transfer (LET). As a first step, beam quality is studied using detectors of varying energy responses. Although the relationship between beam quality (in terms of LET) and response from a single detector (albeit an energy-dependent detector) may not be a unique and monotonic one, by combining signals from several detectors of differing energy responses, sufficient information can be gathered to eliminate degeneracy and to ensure that the detector response can be uniquely described.

Energy dependence of an ionization chamber could be modified by introducing walls made from different materials [1], or by changing the composition of the cavity gas inside the chamber. Using the former technique, we began our investigation by characterizing the response from an Exradin-A12 ionization chamber fitted with geometrically identical walls made from C-552 plastic, aluminum, copper and molybdenum. This is achieved by studying the influence of chamber wall material on correction factors commonly used in clinical reference dosimetry protocols. These corrections must be quantified, and the behavior of ionization chambers must be well characterized prior to us being able to compare the dose response changes of the various wall-material chambers.

The three main correction factors related to acquiring the correct chamber cavity charge readings performed in megavoltage photon and electron beams are the temperature and pressure correction, the polarity correction and the ion recombination factor.

For a given chamber, reversing the polarity of the chamber biasing potential between the two electrodes may lead to different

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charge readings. This phenomenon is referred to as the polarity effect and results from several causes that are classified as either voltage-dependent or voltage independent (Compton current being the main effect).

The ionization chamber charge reading is also influenced by the chamber's collection efficiency, since not all of the ions produced inside the chamber's active volume reach the electrodes. The loss of charge is caused by recombination of ions prior to their collection, which is due to three main effects: initial ion recombination, general ion recombination and ionic diffusion against the electric field.

In initial ion recombination, ions that are produced along the path of a given ionizing particle recombine. Since only a single particle path is considered, this phenomenon is not affected by dose or dose rate unless the number of tracks per unit volume and space-charge density becomes so large that it starts affecting and weakening the collecting electric field strength, or that the tracks begin overlapping. Jaffé [2] explained this effect by assuming that the ions are Gaussian distributed in a column along the path of ionizing particles. Several researchers [3,4] have shown that when initial recombination is dominant, the inverse of charge collected (1/Q) has a linear relationship with inverse of the polarizing voltage across the ion chamber electrodes (1/V).

In general recombination, ions produced in separate tracks (*i.e.* tracks from different ionizing particles) recombine—thus general recombination is dependent on dose rate, since an increase in dose rate increases the number of radiation tracks formed per unit volume and per unit time. Building on the work of Mie [5], Boag and Wilson [6] developed the fundamentals for general recombination and showed that 1/Q varies linearly with $1/V^2$ in continuous radiation beams.

Additionally, it is also possible for ions to diffuse against the electric field and therefore not be collected by the collecting electrode. In such scenarios, it was found that 1/Q follows a linear relationship with 1/V [7].

Due to the imperfect collection of charge caused by ion recombination, the charge $Q(V)$ is smaller than the saturation charge Q_{sat}. The ratio $Q(V)/Q_{sat}$ for a given polarizing potential is defined as the ion collection efficiency $f(V)$ [8]:

$$f(\mathrm{V}) = \frac{Q(V)}{Q_{\mathrm{sat}}} \tag{1}$$

The inverse of the saturation charge Q_{sat} is conventionally determined by linearly extrapolating the curves to $1/V^2 = 0$ and $1/V = 0$, for continuous and pulsed beams, respectively. This linear relationship forms the basis of the "two-voltage" technique, which, as long as the chamber behaves as predicted by Boag theory [9], is recommended by both the AAPM's TG 51's protocol [10] and its Addendum [11], as well as the IAEA's TRS 398 report [12] for the determination of ionization chamber ion recombination in continuous and pulsed external radiation beams.

However, Zankowski and Podgorsak [13] demonstrated that for continuous beams, the linearity between $1/Q(V)$ and $1/V^2$ breaks down in the extreme near-saturation region, slightly above the range ionization chambers are normally operated in during megavoltage machine output measurements (where $f > 0.98$). They have also shown that due to this breakdown, Q_{sat} is underestimated when the measured linear portion of the 1/Q vs. $1/V^2$ plot is extrapolated to $1/V^2 = 0$. This breakdown was also observed in pulsed beams [14].

In this paper we experimentally study the polarity correction and ion recombination of an Exradin-A12 ionization chamber as a function of the chamber wall material. We show how both the magnitude of Q_{sat}, and charge multiplication vary as a function of the atomic number of the wall material. We also attempt to describe our findings using basic principles that have been developed to date and summarized above.

2. Materials and methods

2.1. Experimental methods

The Shonka air-equivalent C-552 plastic wall of an Exradin-A12 0.6 cm^3 Farmer-type ionization chamber (Standard Imaging, Middleton, WI, USA) was replaced by in-house built chamber walls made out of high purity (99.99%) aluminum, copper and molybdenum (see Fig. 1). All chamber walls have a thickness of 0.05 cm and were built to be geometrically identical (with the same wall thickness, cavity length, radius and depth). To prevent electric field distortions, attention was given to ensure that the inner, as well as the outer wall of the chamber were rounded. To ensure reproducibility, two sets of walls were created for each material; one using conventional milling drilling units and another using a computer numerical controlled (CNC) lathe. The selection of the wall materials was based on material atomic number and density, mean excitation energy and electrical conductivity considerations (see Table 1). Since the chamber wall acts as an electrode in the ionization chamber's electrical configuration, sufficient electrical conductivity is necessary to collect the charge produced inside the chamber cavity.

To study polarity and ion recombination, measurements were performed using the Exradin-A12 fitted with all the different wall materials under a continuous Co-60 beam (Theratron-780 Co-60 unit, AECL) as well as a pulsed 6 MV (Clinac 21EX linac, Varian, Palo Alto, CA) photon beams in a Solid Water® phantom (Gammex RMI®, Middleton, WI 53562, USA). Table 2 details the measurement set-up conditions employed.

2.1.1. Polarity

For all chamber wall materials and under both beam types (continuous and pulsed), the polarity correction was determined by measuring the charge at positive and negative 300 V in accordance with both AAPM's Task Group 51 and its Addendum [10,11] as well as the IAEA TRS 398 dosimetry protocol [12].

2.1.2. Ion recombination

As mentioned in Section I, general ion recombination depends on dose rate or dose per pulse. Consequently, k_s (IAEA TRS 398 notation [12], denoted as P_{ion} in AAPM TG51 notation [10,11]), used to correct for the loss of collection efficiency, is calculated differently for continuous and pulsed beams.

Ion recombination was determined for the various walls both using Jaffé-plots, and the 'two voltage technique' (as recommended by AAPM's TG51's protocol and its Addendum, as well as the IAEA TRS 398 reports). Jaffé's theory [2] of recombination allows for the extrapolation of measured data to obtain the saturation charge Q_{sat}. The collection efficiency f is in turn calculated from Q_{sat} using Eq. (1). Additionally, for Co-60 measurements, Q_{sat} values were also determined using the semi empirical model that was proposed by Zankowski and Podgorsak [13], in which they offer a more accurate method of calculating Q_{sat} by accounting for general recombination, as well as, initial recombination, thermal diffusion and charge multiplication. The more comprehensive model is given by:

$$\frac{1}{Q(V)} = \left[\frac{1}{Q_{sat}} + \frac{\alpha}{V} + \frac{\beta}{V^2}\right] e^{-\gamma V} \tag{2}$$

where $Q(V)$ is the measured charge, α and β are curve fitting parameters relating to initial and general recombination, and the exponential term describes charge multiplication with γ being its