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Performance tests and comparison of microdosimetric measurements with four tissue-equivalent proportional counters in scanning proton therapy

J. Farah [a, b, *], M. De Saint-Hubert [c], N. Mojżeszek [d], S. Chiriotti [c], M. Gryzinski [e], O. Ploc [f], F. Trompier [a], K. Turek [f], F. Vanhavere [c], P. Olko [d]

[a] Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Pôle Radioprotection de l'Homme, BP-17, 92260 Fontenay-aux-Roses, France
[b] Hôpitaux Universitaires Paris-Sud, Pôle Imagerie et Médecine Nucléaire, Hôpital du Kremlin-Bicêtre, 78 Rue Général Leclerc, 94270 Le Kremlin-Bicêtre, France
[c] Belgium Nuclear Research Center (SCK-CEN), Boeretang 200, BE-2400 Mol, Belgium
[d] Institute of Nuclear Physics (IFJ-PAN), Radzikowskiego 152, 31-342 Krakow, Poland
[e] National Centre for Nuclear Research (NCBJ), ul. Andrzeja Sołtana 7, 05-400 Otwock, Świerk, Poland
[f] Nuclear Physics Institute (NPI), Department of Radiation Dosimetry, Na Truhlářce 39/64, 180 00 Praha 8, Czechia

HIGHLIGHTS

- Intercomparison of four commercial TEPCs in standard and complex radiation fields.
- Methodology to convert propane to propane-TE spectra and extrapolate low-LET events.
- TEPCs provide critical data to monitor proton therapy's stray radiation environment.
- HAWKs' proton edge position, set by the manufacturer, remains controversial.
- Calibration and processing of TEPCs involve several challenges and open questions.

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ABSTRACT

This paper compares the performance of four different Tissue-Equivalent proportional counters (TEPC) first in standard radiation fields, with gamma and neutron sources, then in the mixed and complex/intense neutron and photon stray radiation field of a scanning proton therapy facility. The paper focuses on the dead time correction and introduces a new spectra processing methodology to enable the comparison of the four TEPCs while accounting for their different gas filling and gain, lineal energy range of the spectrum and the analysis methodology. Measurements with ^{137}Cs and/or ^{60}Co gamma sources demonstrate variable low-LET threshold for each TEPC while data acquired with a ^{252}Cf neutron source show comparable response of the four TEPCs for high-LET particles. Meanwhile, in the scattered field of proton therapy, microdosimetric spectra measured at different positions and orientations around the patient show a majority of high-LET events at the smallest angle with respect to the beam axis while low-LET particles were mainly dominant at 90° from the beam axis. The introduced processing methodology led to good overlapping of microdosimetric spectra for the four systems.

1. Introduction

Microdosimetric measurements with Tissue-Equivalent proportional counters (TEPC) are a well-established method for sound dosimetry in complex radiation fields (Rossi and Zaider, 1994; Waker, 1995; Siebers et al., 1992; Bottollier-Depois et al., 2004). The advantage of using TEPCs compared to other dosimeters is their capability to measure the lineal energy (y) spectrum which enables

* Corresponding author. Hôpitaux Universitaires Paris-Sud, Pôle Imagerie et Médecine Nucléaire, Hôpital du Kremlin-Bicêtre, 78 Rue Général Leclerc, 94270 Le Kremlin-Bicêtre, France.
E-mail address: jad.farah@aphp.fr (J. Farah).

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the characterization of the Lineal Energy Transfer (LET) in mixed radiation fields. TEPCs are also known to have a quite stable neutron dose equivalent response (within 15%) for neutrons below 200 MeV (Alexeev et al., 1998) and are therefore of particular interest for applications in the medical field.

In proton therapy for example where secondary neutrons of hundreds of MeV may be encountered, the microdosimetric approach enables the measurement of radiation dose deposition in tissue-equivalent material as well as the evaluation of radiation quality factors and help deriving good estimates of the Relative Biological Effectiveness (RBE) of the therapeutic beam (Loncol et al., 1994; Binns and Hough, 1997; Coutrakon et al., 1997; De Nardo et al., 2004; Agosteo et al., 2008; Yonai et al., 2010; Rollet et al., 2011). In addition, TEPCs have been used for shielding studies and to monitor the stray radiation environment inherent to both scattering and scanning proton therapy facilities (Perez-Andujar et al., 2012; Farah et al., 2014, 2015). Finally, the rather simple implementation of TEPCs is also a major asset in characterizing proton therapy's stray radiation environment when compared to cumbersome and complex Bonner Sphere spectrometry systems (BSS).

However, a deep knowledge of the radiation physics and interaction mechanisms at the micro metric scale is required to make full use of TEPCs and the microdosimetric approach; this is less critical when using regular and extended-range proportional counters. Additionally, TEPCs suffer from an extreme sensitivity to measurement conditions which can strongly affect the lineal energy spectrum. A known effect due to dead time is the spectra distortion due to pile up of pulses (Aslam et al., 2011). Finally, TEPC-specific physical properties and acquisition features such as gas filling, site size, gas gain settings, etc. render the intercomparison of microdosimetric data difficult when different TEPCs are at use. All these considerations strongly impact the overall measurement uncertainties especially in the intense stray radiation field of proton therapy.

This work addresses the above mentioned challenges while comparing four of the most commonly used TEPCs including three different versions of the HAWK system and one LET-SW5 TEPC, all manufactured by the Far West Technology (FWT Inc., USA). The paper first recalls the different calibration procedures, introduces a new dead time correction approach and focuses on the spectra processing methodology for the comparison of the four TEPCs. Results shown here involve measurements done in standard radiation fields using ^{137}Cs and/or ^{60}Co gamma sources to check the low-LET threshold of each TEPC. Measurements with ^{252}Cf and ^{241}Am-Be neutron sources are also shown to visualize the position of the proton edge in the presence of high-LET particles. Finally, measurement results in the stray radiation field of a spot scanning proton beam are shown while simulating a brain tumor treatment and considering a 5-years old anthropomorphic phantom. In this case, the paper also compares TEPC H values against $H^*(10)$ data from other instruments such as the extended-range Wendi-II rem-counter (Olsher et al., 2000).

2. Materials and methods

2.1. TEPC systems

In this study, three HAWK systems (versions 1, 2 and 3) and one LET-SW5 TEPC were used (Cf. Table 1). These systems are all made of A-150 conducting tissue equivalent plastic, have identical spherical volume (12.7 cm-diameter) and simulate a site size of 0.2 mg/cm^2, corresponding to a site diameter of 2 μm at density of 1 g/cm^3. The four TEPCs are however physically different in their gas composition and the acquisition shows differences in gas gain, energy binning and resolution, etc. HAWK TEPCs have an integrated system for the processing of microdosimetric spectra and absorbed/equivalent dose calculations and display while the LET-SW5 TEPC requires manual data processing.

2.2. Calibration, dead time correction and spectra analysis

2.2.1. Lineal energy calibration

TEPCs measure the pulse height spectrum due to charged particles that ionize the gas. A multichannel analyzer (MCA) measures the pulse size detected and processes the signal. After processing the raw TEPC data is possible to obtain the so-called microdosimetric spectrum in which the dose distribution is usually plotted as yd(y) against log(y) (ICRU, 1983).

Specific features of the microdosimetric spectrum such as the electron, proton and alpha edges can be used for calibration purposes. The proton edge corresponds to the maximum energy imparted by a recoil proton in a given cavity and is generally used for calibration of the y scale. In fact, the raw pulse height spectra are calibrated versus lineal energy (y) by adjusting the y scale to the proton edge position ($y_{p\text{-}edge}$). According to the manufacturer, the proton edge should rise at 150 keV μm^{-1} in lineal energy for a 0.2 mg cm^{-2} mass site size cavity filled with C_3H_8 (HAWKs). Meanwhile, for LET-SW5 with an identical site sized cavity filled with C_3H_8-TE, the proton edge should be at 136 keV μm^{-1}.

For HAWKs, during the initial calibration performed by the manufacturer, the gas gain is adjusted by changing the high voltage of the TE plastic chamber so that channel 100 in the spectrum corresponds to ~150 keV μm^{-1}. Then, as the gas gain voltage is fixed and becomes inaccessible for HAWK end-users, these check the calibration adequacy of their system before each measurement by verifying the position of the proton edge using an internal ^{244}Cm source. When a shift in the proton edge position is observed, the TEPC should be sent back to FWT for refilling the gas counter and subsequent re-calibration. Alternatively, for the LET-SW5 TEPC, the microdosimetric spectra calibration adjustment can be performed by the user with an internal ^{244}Cm source emitting 5.8 MeV alpha particles (Schrewe et al., 1988). The imparted energy, ε, by this source is known (172 keV in a 0.2 mg cm^{-2} mass site size) and is used to convert channels to y (keV μm^{-1}) using the following relationship which holds for a spherical TEPC: $y = \frac{\varepsilon}{\frac{2}{3}d}$ where d is the simulated site size.

2.2.2. Dead time correction

HAWK TEPCs are well known to suffer from an extreme sensitivity at measurement conditions where a dead time value > 25% can lead to large distortions in the lineal energy spectrum (Aslam et al., 2011). It is hence necessary to compute the dead time value whenever high dose rates may be encountered as in the proton therapy field.

For HAWK systems, the dead time value is calculated from the number of counts using the equation provided by FWT in the users' manual: dead time = 1/[1-(N*1.07*10^{-6})] where N is in counts per minutes. HAWKs v. 2 and v. 3 automatically compute this dead time correction factor while this is not the case for HAWK v. 1. Absorbed dose and equivalent dose values are then simply multiplied by this coefficient to correct for dead time. However, as the relationship between the number of counts and the dose is not linear, especially considering the different particle types and LETs, such a correction is not fully satisfactory. A proper management of dead time would indeed require an appropriate correction of microdosimetric spectra differently for low and high-LET events.

Hence in this work, the number of low-LET and high-LET counts was separately used to calculate two dead time correction factors which were then specifically used to multiply the high-gain (low-