Published in final edited form as:

Radiat Meas. 2008 October ; 43(9-10): 1498–1505. doi:10.1016/j.radmeas.2008.09.003.

A comparison of the measured responses of a tissue-equivalent proportional counter to high energy heavy (HZE) particles and those simulated using the Geant4 Monte Carlo code

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Abstract

Monte Carlo simulations of heavy ion interactions using the Geant4 toolkit were compared with measurements of energy deposition in a spherical tissue-equivalent proportional counter (TEPC). A spherical cavity with a physical diameter of 12.7 mm was filled with propane-based tissue-equivalent gas surrounded by a wall of A-150 tissue-equivalent plastic that was 2.54 mm thick. Measurements and Monte Carlo simulations were used to record the energy deposition and the trajectory of the incident particle on an event-by-event basis for ions ranging in atomic number from 2 (⁴He) to 26 (⁵⁶Fe) and in energy from 200 MeV/nucleon to 1000 MeV/nucleon. In the simulations, tracking of secondary electrons was terminated when the range of an electron was below a specified threshold. The effects of range cuts for electrons at 0.5 μ m, 1 μ m, 10 μ m, and 100 μ m were evaluated. To simulate an energy deposition influenced by large numbers of low energy electrons with large transverse momentum, it was necessary to track electrons down to range cuts of 10 μ m or less. The Geant4 simulated data closely matched the measured data acquired using a TEPC for incident particles traversing the center of the detector as well as near the gas-wall interface. Values of frequency mean lineal energy and dose mean lineal energy were within 8% of the measured data. The production of secondary particles in the aluminum vacuum chamber had no effect on the response of the TEPC for ⁵⁶Fe at 1000 MeV/nucleon. The results of this study confirm that Geant4 can simulate patterns of energy deposition for existing microdosimeters and is valuable for improving the design of a new generation of detectors used for space dosimetry and for characterizing particle beams used in hadron radiotherapy.

Keywords

Tissue-equivalent proportional counter; Microdosimetry; Heavy ions; HZE; TEPC; Geant4

1. Introduction

The radiation environments in space and near hadron radiotherapy fields are compositionally complex and temporally dynamic. For example, particle intensities associated with galactic

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cosmic radiation (GCR) and solar particle events (SPEs) are dominated by protons and helium ions, but they also have a measurable component from particles of high atomic number and high energy (HZE) that have sufficient ranges to penetrate shielding, delivering substantial radiation doses to the skin, blood-forming organs, and other radiosensitive organs (Wefel, 1978). The characteristics of the incident particles change with depth in absorbing materials because of the slowing-down process and fragmentation.

Because these fields are complex and dynamic, particular attention must be paid in monitoring radiation exposure. Radiological protection policies require that effective dose be assessed to demonstrate compliance to regulations. This assessment includes measuring absorbed dose and applying radiation weighting factors or quality factors that are used to estimate the detriment from complex radiation fields. An ideal radiation monitoring system in space would provide real-time determinations of absorbed dose and estimates of radiation quality so that effective dose as a function of time could be assessed, which would then provide a warning when the dose rate exceeds action levels related to SPEs or other mitigating circumstances. Developing such a monitoring system is a formidable task because the dose rate can vary from 1 $\mu\text{Gy/h}$ to 500 mGy/h and the distribution of *LET* for GCR and SPEs can range from 0.2 $\text{keV}/\mu\text{m}$ to more than 300 $\text{keV}/\mu\text{m}$. Another important consideration is that *LET* describes the transfer of energy at a point along the trajectory of the particle. This is a satisfactory description of energy deposition for particles with low velocities, such as alpha emissions from radioactive materials. However, typical HZE particles can have high velocities (e.g., $\beta > 0.5$) that generate high energy recoil electrons, or “delta rays,” that extend large distances from the track of the primary particle. This creates a distribution of energy deposition events in volumes of material that have biological significance at the cellular and molecular level. The biological effectiveness of the radiation depends on the density of ionization along the track of the incident particle, or the *LET* of the particle.

Rossi and Rosenzweig (1955) developed the concept of a tissue-equivalent proportional counter (TEPC) to measure the energy deposited in simulated volumes of tissue with dimensions similar to those of the nucleus of a mammalian cell. The TEPC has been used as a microdosimeter on high-altitude aircraft flights, near high energy particle accelerators, in or near therapeutic beams, and in space. A TEPC does not record *LET* directly. Instead, it measures individual energy deposition events, ε , that depend on *LET* and the trajectory of the particle through a simulated volume, which is often shaped as a sphere or cylinder. Energy deposition, ε , is then converted into lineal energy, y , which has the same dimensions as *LET*. Thus, the TEPC is a particularly useful microdosimeter in mixed or unknown radiation fields. Likewise, an understanding of the response of a TEPC can provide information relating to the nature of the interactions that these particles have in biologic materials.

The technology of the TEPC has developed over the years, making TEPCs reliable dosimeters for measuring absorbed dose and estimating quality factors in mixed radiation fields. The conventional TEPC used today has a rigid wall made of tissue-equivalent (TE) plastic surrounding a gas-filled cavity. The National Aeronautics and Space Administration (NASA) has developed TEPC-based flight instruments that have been used during manned space missions on the Space Transport Shuttle and International Space Station (Badhwar, 2002). For these instruments, it was assumed that a measured value of lineal energy, y , was numerically equal to *LET*, and $f(y)$ was considered to be the *de facto* distribution $f(LET)$ incident upon the detector (Badhwar et al., 1994a, b; Doke et al., 2001).

Ground-based investigations have been made of the response of a spherical TEPC to incident HZE particles that are characteristic of the GCR spectrum (Rademacher et al., 1998; Gersey et al., 2002; Borak et al., 2004; Guetersloh et al., 2004; Taddei et al., 2006). The purpose of these studies was to characterize patterns of energy deposition that can be influenced by the

track structure associated with high energy delta rays. The objectives were to determine if the conditions for measuring absorbed dose were satisfied as well as the extent to which patterns of energy deposition could be used to estimate quality factors. In these studies, every effort was made to ensure that interpretations of the data were true reflections of the response of the detector and to distinguish between the physics of energy deposition in homogeneous tissue and artifacts of TEPC design.

Recently it has become possible to simulate computationally the response of a TEPC to HZE particles. Powerful computer codes have been developed for large-scale, accurate, and comprehensive simulations of particle detectors used in complex physics experiments. The Geant4 Monte Carlo toolkit simulates the passage of particles through matter (Agostinelli et al., 2003; Allison et al., 2006). All aspects of the simulation process have been incorporated, including a detailed presentation of the geometry, the materials involved, and the fundamental properties of the particles of interest.

The objectives of this study were to compare Monte Carlo results with experimental measurements and to explore the extent to which this process can be used to improve the design of the next generation of TEPCs. These objectives were accomplished by simulating the response of a spherical TEPC in terms of the energy deposited in the gas cavity for HZE particles ranging in energy from 200 to 1000 MeV/nucleon and in atomic number from 2 (^4He) to 26 (^{56}Fe) using the Geant4 Monte Carlo toolkit.

2. Materials and methods

2.1. Experimental arrangements

All experiments were performed at the Alternating Gradient Synchrotron (AGS) located at the Brookhaven National Laboratory in Upton, NY, and at the Heavy Ion Medical Accelerator (HIMAC) operated at the National Institute of Radiological Sciences in Chiba, Japan. The same spherical TEPC (Far West Technology, Inc., Goleta, CA) was used in all experiments. The TEPC had a sensitive volume diameter of 12.7 mm and a TE wall thickness of 2.54 mm. The sensitive volume was filled with a propane-based TE gas at a pressure of either 4.4 kPa to simulate a tissue diameter of 1 μm for high-*LET* particles or 13.2 kPa to simulate a tissue diameter of 3 μm for low-*LET* particles. The anode wire extended through the center of the gas cavity and was surrounded by a helical grid wire that formed a uniform electric field near the anode for ion-pair multiplication. Calibration was accomplished using an internal ^{244}Cm alpha particle source with a gravity-controlled gate. Calibrations were also performed using the maximum energy deposition from recoil protons generated in the wall using fast neutrons from an external Pu-Be source; values of 96.8 keV and 251.6 keV were applied for simulated diameters of 1 μm and 3 μm , respectively. The two methods agreed to within 2%.

Fig. 1 shows a general schematic diagram of the experimental setup. In all cases, the TEPC was positioned within a charged particle spectrometer that measured individual particle events during the experiment. Four pairs of position-sensitive silicon detectors (PSDs; denoted PSD1–PSD4 in Fig. 1) and a 3-mm-thick lithium-drifted silicon detector (labeled “3 mm” in Fig. 1) were used to track the position, energy, and type of each particle as it passed through the TEPC. The transverse coordinates (X , Y) of each incident particle were recorded both upstream and downstream of the TEPC. These data were used to reconstruct the trajectory of the particle through the TEPC and to estimate the impact parameter, b , which was defined as the radial distance (in mm) from the central beam axis (i.e., the center of the TEPC) to the position of particle as it traversed the mid-plane of the TEPC. For particles with $LET > 10 \text{ keV}/\mu\text{m}$, the spatial resolution of the system was $\sim 10\%$. Additional details about this experimental setup have been published elsewhere (Wong et al., 1990; Zeitlin et al., 1994; Rademacher et al., 1998; Gersey et al., 2002; Guetersloh et al., 2004; Taddei et al., 2006).

Because only particles with the appropriate rigidity will survive magnetic transport to the experimental room, the energy of the particle beam as it exited the accelerator and passed through the beam transport system was accurately known for each experiment. Calculations were performed using a numerical approximation of the Bethe-Bloch equation to determine energy lost in each component located upstream of the TEPC (Taddei, 2005). As a result, we were able to determine the precise energy of the particles as they entered the gas cavity of the TEPC.

Data were collected on-line with a Computer Automated Measurement and Control (CAMAC) based data acquisition system that can process and store signals from up to 30 analog-to-digital converters. A coincidence between the TEPC signal and a signal from one of the silicon-based detectors triggered the acquisition system. Data were processed on an event-by-event basis. For each experiment, data for a minimum of 500,000 triggers were recorded and stored on disk for subsequent analysis. After the data acquisition was completed, the stored information was processed off-line such that each event could be interrogated and analyzed individually. Extensive details about the data acquisition and analysis have been published elsewhere (Rademacher et al., 1998; Gersey et al., 2002; Guetersloh, 2003; Guetersloh et al., 2004; Taddei, 2005; Taddei et al., 2006).

2.2. Computational procedures

Monte Carlo simulations were performed using the Geant4 particle transport toolkit (version 4.7.1) (Agostinelli et al., 2003; Allison et al., 2006). The simulations were designed to match the experimental conditions. The particle source was a uniform, parallel beam of fully stripped ions beginning 2 cm upstream of the center of the TEPC and having a diameter of 17.78 mm. Simulations were performed separately for each particle type and energy combination: ^4He at 230 MeV/nucleon; ^{12}C at 220 and 390 MeV/nucleon; ^{16}O at 390 MeV/nucleon; ^{28}Si at 380 MeV/nucleon; and ^{56}Fe at 200, 360, 540, 700, 790, and 1000 MeV/nucleon. The *LET* of these particles in water ranged from 1.68 keV/ μm to 214 keV/ μm .

We tried to ensure that the geometry of the TEPC used in the simulations matched that of the actual TEPC used during the experiments. Thus, the geometric model of the spherical, walled TEPC was composed of a 12.7-mm-diameter sphere of low-pressure gas surrounded by a 2.54-mm-thick solid, spherical wall. The gas was composed of a propane-based TE gas. The pressure of the gas was consistent with that of the corresponding experiments. A 1- μm -diameter sphere of tissue simulated by setting the pressure of the gas to 4.4 kPa for all simulations, except for those of 230 MeV/nucleon ^4He and 220 MeV/nucleon ^{12}C , in which the pressure was set to 13.2 kPa to simulate a 3- μm -diameter sphere of tissue. The solid wall of the simulated TEPC was composed of A-150 TE plastic. The remainder of the world volume was filled with air of standard density and pressure.

The same physics list was used for all simulations. This physics list was a compilation of the physics lists from the N03, underground physics (Howard and Araujo, 2003), and radioprotection (Cougnet et al., 2004) examples included in the Geant4 toolkit. The latter (specifically, with the Bertini Cascade option) was used for hadronic interactions; low energy physics models were implemented for all particles.

To increase the efficiency of the particle transport using the Geant4 code, we specified a threshold in terms of range, or a "range cut," for electron transport so that when an electron slowed down to an energy that corresponded to a range that was below the specified range cut, the remaining energy of the particle was deposited locally and the particle was no longer tracked. For ionization events with HZE particles, the velocity of the incident particle is sufficient to eject energetic secondary electrons (i.e., delta rays) and numerous soft electrons. To simulate a tissue diameter of 1 μm within the gas cavity of physical diameter 12.7 cm, the

density of the gas was 0.000079 g/cm³. Thus, the range of electrons in the TE gas was much larger than that of electrons in the TE wall, which had a density of 1.127 g/cm³. It was therefore important to select an appropriate range cut for delta rays that would result in a realistic response of the gas-filled detector. To investigate the effect of low energy delta rays on the response of the TEPC, we varied the range cut for electrons between 0.5, 1, 10, and 100 μm for ⁵⁶Fe at 360 MeV/nucleon and between 10 and 100 μm for ⁵⁶Fe at 1000 MeV/nucleon. For all other simulations, the range cut for electrons was increased to 100 μm to achieve faster simulation times (i.e., to reduce variance).

A recent study by Beck et al. (2006) showed that the vacuum chamber for a TEPC may influence its response in some radiation fields. In an operational TEPC, a metal shell is used to maintain the vacuum. To investigate the effect of the aluminum vacuum shell on the response of the TEPC used in our study, we performed separate simulations for ⁵⁶Fe at 1000 MeV/nucleon with a 0.18-mm-thick aluminum shell added to the geometric model. This energy was chosen because it was the maximum energy for all the simulations, which, in turn, produces delta rays with the highest energy (and range). The aluminum shell was modeled as a hemisphere surrounding half of the TEPC, with a cylindrical sleeve extending past the remaining portion of the detector. The detector was oriented so that the cylindrical axis was perpendicular to the direction of the beam. Simulations were performed using range cuts of 10 μm and 100 μm .

In both the simulations and the measurements, the location of each incident particle was recorded as it traversed the mid-plane of the TEPC. In the simulations, the location of the incident particle as it traversed the mid-plane of the TEPC was assumed to be equal to its initial position. The radial distance from the central beam axis (i.e., the center of the TEPC) to the position of the particle as it traversed the mid-plane of the TEPC was defined as the impact parameter, b . For instance, for particles that traversed the center of the TEPC, $b = 0$; for particles that traversed the TEPC at the gas-wall interface, $b = 6.35$ mm. The maximum impact parameter for the simulated beams was $b = 8.89$ mm, corresponding to the outer edge of the TE wall. Just as the relationship between energy deposition patterns and the impact parameter of the incident particle had been investigated in the previous experiments, we also investigated this relationship using the simulated data collected in this study.

2.3. Dosimetric analysis

The initial position of the incident particle and the energy deposited in the gas cavity (i.e., the sensitive volume of the detector) were recorded for each particle history. The energy imparted to the gas simulated the response of the TEPC for each incident particle. In microdosimetry, it is helpful to evaluate the response of the detector as a function of lineal energy, y , which is related to the *LET* of the particle and, thus, can be used to calculate absorbed dose and to estimate the quality of the radiation. Lineal energy is defined as

$$y = \frac{\varepsilon}{\bar{l}}, \quad (1)$$

where ε is energy deposited in an event and $\bar{l}$ is the mean chord length of the sensitive volume that results if it is randomly intersected by straight lines, i.e., in the condition of μ -randomness.

As mentioned above, the simulated response of the TEPC was characterized in terms of the energy deposited in the gas cavity for each event. For each type of incident particle, the response functions of the TEPC were simulated as energy deposition distributions and lineal energy distributions. Mean values of the lineal energy distributions were calculated. The frequency

mean lineal energy, $\overline{y_f}$ can be used to estimate the absorbed dose; it is defined as the first moment of y ,

$$\overline{y_f} = \int y f(y) dy. \quad (2)$$

The simulated $\overline{y_f}$ was used as a figure of merit to compare with the measured $\overline{y_f}$ to evaluate if the Geant4 simulations adequately estimated the absorbed dose. The dose mean lineal energy, $\overline{y_d}$, is related to the quality of the radiation; it is defined as the second moment of y divided by the first moment,

$$\overline{y_d} = \frac{\overline{y^2}}{\overline{y}} = \frac{\int y^2 f(y) dy}{\int y f(y) dy}. \quad (3)$$

The simulated $\overline{y_d}$ was used as a figure of merit to compare with the measured $\overline{y_d}$ to evaluate if whether the Geant4 simulations adequately estimated the quality of the radiation.

3. Results and discussion

3.1. Energy deposition from events with $b < 0.5$ mm

For this TEPC, particles with $b < 1$ mm, would have a trajectory through the gas cavity ranging in diameter from 12.5 mm to 12.7 mm. Given the spatial resolution of the PSDs, particles with a measured $b < 0.5$ mm had trajectories that varied $< 2\%$ from the diameter. If the energy deposited in an event was simply equal to the energy transferred by the incident particle, a first approximation of the energy deposited would be the product between the *LET* and the path length through the gas cavity, dx , and the energy deposition for these events would be approximately $\varepsilon = LET \text{ diameter}$ for particles with $b < 0.5$ mm. This does not take into account energy enhancement from delta rays entering the gas cavity and energy loss due to delta rays escaping the gas cavity.

The simulated tracks of a particle passing through the center of the gas cavity and of secondary particles generated during this event are illustrated in Fig. 2. The tracks of the delta rays are red. This figure clearly shows that delta rays are entering and exiting the gas cavity.

Fig. 3 shows the response of the TEPC for ^{56}Fe particles at 360 MeV/nucleon ($\beta = 0.69$, $LET = 214$ keV/ μm), with $b < 0.5$ mm, at a tissue diameter of 1 μm . The solid curve represents the results for the Geant4 calculation, with a range cut of 100 μm . The peak value occurred at 170 keV, with a full width at half maximum (FWHM) of 19 keV (i.e., 11%). When the range cut was changed to 1 μm , the peak value increased to 176 keV ($\sim 4\%$ increase) and the FWHM increased to 21 keV (i.e., 12%). Fig. 3 also shows the response of a TEPC to ^{56}Fe particles at 360 MeV/nucleon measured by Gersey et al. (2002). The peak value occurred at 170 keV, with an FWHM of 29 keV (i.e., 17%). The measurements and the calculations show that, on average, the energy deposited in the gas cavity for particles with $b < 0.5$ mm is about 80% of the value expected from *LET* and path considerations alone. This indicates that more energy escaped the gas cavity from high energy delta rays than entered the gas cavity from delta rays emerging from the upstream wall. There is a pronounced difference in the variance between the measured data and the data simulated using Geant4. The increased spread in the peak region of the measured data is due to the variance in the gas multiplication for the physical proportional counter, which was not included in the Monte Carlo computation. The measured data also have a broad tail with some patterns of energy depositions > 200 keV. These events have been shown

previously to represent enhanced energy depositions for ^{56}Fe particles that intercept the anode wire or helical grid wire. Such enhanced energy depositions are artifacts that resulted from the design of the proportional counter.

Analysis of events in which the incident particle traveled through the center of the TEPC was expanded to ^{56}Fe particles at different energies. Data from the experiments and simulations are shown in Table 1. The coefficient of variation in each simulated data set, i.e., the quotient of the standard deviation and the mean, was $<6\%$. Excellent agreement ($<2\%$) was observed between the mean energy deposited of the measured data and that of the data simulated using Geant4.

3.2. Energy deposition from events of all impact parameters

We used the Geant4 toolkit to simulate a uniform fluence of ^{56}Fe particles at 360 MeV/nucleon. The results were sorted according to energy deposited in the gas cavity as a function of impact parameter (Fig. 4). Measurements with a TEPC were analyzed in a similar fashion (Gersey et al., 2002). For small impact parameters (i.e., $b < 4$ mm), the Geant4 simulated and the measured data show that energy deposition was less than that predicted by $LET \cdot dx$ alone. The reason for this discrepancy is that more delta rays escape the gas cavity than enter it after being generated in the upstream wall of the TEPC. For large impact parameters (i.e., $b > 5.5$ mm), the energy deposition was larger than predicted from $LET \cdot dx$ alone. This effect has been interpreted as an influx of numerous low energy delta rays generated when the incident particle passes through the wall of the TEPC where the vector normal to the surface begins to point in a direction transverse to the direction of the incident particle. There is a pronounced peak when the impact parameter is almost exactly at the gas-wall interface (i.e., $b = 6.35$ mm). The peak is very narrow because a slight increase in the impact parameter places the origin of these soft electrons deep enough in the wall that they cannot escape and deposit their energy within the gas cavity.

3.3. Varying the range cut for electrons

In the Monte Carlo simulations, we were able to terminate artificially the transport of delta rays for selected range cuts, which is impossible to do during actual measurements. Thus, we investigated the effect of the range cut for electrons on the response of the TEPC using the Monte Carlo calculations. Fig. 5 shows simulated events for ^{56}Fe at 360 MeV/nucleon that have been grouped into narrow bins of impact parameter; each point represents the average energy deposition for each bin. As the range cut was increased, the particles with impact parameters between 5.8 mm and 6.3 mm showed a decrease in energy deposition because more low energy delta rays were stopped in the wall, so none of their remaining energy was deposited in the gas cavity. There was a valley, or minimum, in energy deposition in this region of impact parameters that was affected by the range cut. This effect was dramatically evident when the impact parameter was approximately equal to the radius of the gas cavity, 6.35 mm. Furthermore, when the range cut for electrons was set to 100 μm , the spike of large energy deposition disappeared completely.

There have been some concerns with this interpretation of enhanced energy deposition at the gas-wall interface. For instance, it has been argued that this spike in energy deposition is the result of recoil target nuclei generated by nuclear elastic scattering of the primary particle rather than from low energy delta rays. Rademacher et al. (1998) analyzed these events using capabilities of the spectrometer system shown in Fig. 1. Nuclear scattering events would correspond to a measurable change in the trajectory of the incident particle. Differences in the direction cosines for the incident particle before (PSD1 and PSD2) and after the TEPC (PSD3 and PSD4) were similar to events outside of the pronounced peak of energy deposition. This and the frequency of events estimated from the mean free path for nuclear elastic scattering provided evidence that recoil nuclei were not responsible for this enhanced energy deposition.

Monte Carlo simulations also showed that enhanced energy deposition from delta rays could be observed when the impact parameter of the incident particle was near the radius of the gas cavity (Nikjoo et al., 2002). Fig. 6 shows a single event generated by Geant4 for such an incident particle, with $b = 6.35$ mm, that grazes the gas-wall interface. The large influx of delta rays is clearly evident. This confirms the hypothesis that these events are mainly due to delta rays, not recoil target nuclei, entering the gas cavity.

Fig. 7 shows the response function from measurements made using the TEPC for a uniform fluence of ^{56}Fe at 360 MeV/nucleon. The large number of events with energy deposition < 20 keV was due to particles that passed through the wall of the TEPC but missed the gas cavity (i.e., particles with $b > 6.35$ mm). For the measured TEPC data, events with energy depositions significantly $> \sim 214$ keV (i.e., $LET \cdot \text{diameter}$) were from particles grazing the gas-wall interface and those colliding with the anode wire or helical grid wire. The region of energy deposition between 30 keV and 210 keV are events from particles that passed through the gas cavity. The measured data show that events were suppressed in the lower part of this region (i.e., between 30 keV and 100 keV). These energy depositions would be expected to occur for events with b ranging from 5.5 mm to 6.3 mm. However, the enhancement in energy deposition in this region was from electrons originating in the wall of the TEPC that reached the gas cavity. The wall in this region of the detector curves considerably in the transverse direction. The resulting influx of soft electrons therefore shifted the energy deposition towards larger values (> 90 keV).

The results from the Geant4 simulated data show a series of thresholds in the region between 30 keV and 100 keV. When the range cut was 100 μm , most low energy electrons generated in the wall were stopped in the wall, so energy deposition was more or less related to the path length through the gas cavity. When the range cut was decreased to 10 μm , electrons were transported farther; therefore, more of them entered the gas cavity resulting in an enhancement of energy deposition. The threshold at ~ 70 keV corresponds to the valley of the plot of energy deposition vs. impact parameter shown in Fig. 5. When the range cut was decreased to 1 μm , the threshold was shifted to ~ 90 keV, which is consistent with the results shown in Fig. 5 and more accurately simulates the actual response of the TEPC.

3.4. Lineal energy

Data were then evaluated to determine the complete response function of the TEPC for a uniform fluence of particles. The response function was used to determine the distribution of events in terms of lineal energy, y , which then was used to compute the frequency mean lineal energy, $\bar{y}_f$, and dose mean lineal energy, $\bar{y}_d$, for the incident particles.

Table 2 summarizes the mean lineal energy values obtained from the TEPC measurements and the Monte Carlo simulations for ^{56}Fe at 360 MeV/nucleon. These results show that, for all range cuts that were tested, the estimates of $\bar{y}_f$ and $\bar{y}_d$ using Geant4 were within 7% of the measured values for ^{56}Fe at 360 MeV/nucleon. Thus, for the purpose of calculating $\bar{y}_f$ and $\bar{y}_d$, a range cut of 100 μm was used for all of the other particle types.

As described in Section 2.2, computations of full response functions for a spherical TEPC were performed for ^4He , ^{12}C , ^{16}O , ^{28}Si and ^{56}Fe with LET ranging from 1.68 keV/ μm to 214 keV/ μm with a range cut of 100 μm . Results in terms of mean lineal energy are listed in Table 3. All values of $\bar{y}_f$ and $\bar{y}_d$ computed using Geant4 were within 8% of the measured values. Therefore, for a broad range of particle types, energies, and LET , a range cut of 100 μm for electrons was sufficient to reproduce the measured mean lineal energy values.

These Geant4 simulations of the spherical TEPC included only a TE plastic wall and a TE gas cavity. Thus, to determine what effect the vacuum chamber has on the response of this particular TEPC, we investigated the patterns of energy deposition in the gas cavity both with and without

the aluminum shell that is used to maintain the vacuum. Simulations were performed for ^{56}Fe at 1000 MeV/nucleon with an aluminum shell that was 0.18-mm-thick using range cuts of 10 μm and 100 μm . There were no differences between the response functions with and without the aluminum vacuum chamber. This observation differs from that of Beck et al. (2006), who found that the presence of the vacuum chamber altered the response of the TEPC. This is because the TEPC used in their study had a much thicker vacuum chamber made of stainless steel while the aluminum vacuum chamber of the TEPC used in our study was thin.

4. Conclusions

In this study, we evaluated the patterns of energy deposition in a spherical TEPC exposed to HZE particles using Geant4 Monte Carlo simulations and measured data from accelerator-produced particles. The objectives were to verify the interpretation of observations from experimental data and to determine if a TEPC is capable of measuring absorbed dose and estimating radiation quality for the broad range of particles and *LET* associated with GCR. This can also validate the extent to which Geant4 calculations can be used to improve the design of the next generation of TEPCs.

The process entailed first analyzing energy deposition for specific conditions, such as the trajectory of the incident particle through the detector, and then combining all events into response functions that were used to estimate dosimetric quantities based on lineal energy.

Conventional dosimetry using gas-filled detectors for low-*LET* electrons and photons is based on satisfying conditions of charged particle equilibrium. For free-in-air measurements, these conditions are satisfied by making the thickness of the wall and build-up cap similar to the effective range of the electrons. HZE particles with energies up to 1000 MeV/nucleon can generate high energy electrons with ranges >15 mm in TE materials. However, the differential energy spectrum is not uniform. It is predominated by very low energy electrons in the transverse direction, with ranges <1 μm . The high energy electrons are preferentially produced in the forward direction. Track structure models for ^{56}Fe at 1000 MeV/nucleon indicate that 50% of the dose is delivered within 10 nm of the trajectory of the particle (Chatterjee et al., 1973; Chatterjee and Schaefer, 1976; Cucinotta et al., 1995). This has pronounced implications for the wall thickness required for gas-filled detectors.

In this study, the TEPC had a TE wall thickness of 2.54 mm. Particles passing through the center of the detector (i.e., $b = 0$, $dx = 12.7$ mm) penetrate this amount of plastic before entering the gas cavity. As particles traverse the upstream wall, secondary electrons are generated in the upstream wall, but this enhancement in energy deposition is not sufficient to create charged particle equilibrium because these secondary electrons are mostly high energy delta rays that do not deposit all of their energy in the gas cavity. The response of the TEPC from measurements and Geant4 simulations agree in terms of the mean energy deposited in the gas cavity for ^{56}Fe particles with a large range of energy. However, the width (FWHM) of the distribution was greater for the measurements than the computations. The Monte Carlo simulations included only the stochastic nature of energy deposition, whereas the measurements included uncertainties in position and variations in gas multiplication from event to event.

Energy deposition remained suppressed for particles with small impact parameters covering more than 50% of the central projected area of the spherical gas cavity. However, for particles with larger impact parameters, with correspondingly smaller path lengths, energy deposition was greater than what would be predicted from the product of *LET* and path length alone. This study has clearly confirmed what had previously been concluded from measurements: that the enhancement in energy deposition for particles with large impact parameters is from soft

electrons with sufficient transverse momentum to reach the gas cavity because of the curvature of the TEPC wall. There is a very large enhancement of energy deposition for particles that just graze the gas-wall interface (i.e., those with impact parameter = radius), where many soft electrons reach the gas cavity. This peak was observed in the measured data and confirmed with the Geant4 simulated data. However, in the Monte Carlo simulations, it was necessary to track low energy electrons by reducing the range cut to 10 μm or smaller.

The measured data and computational results were placed into a spectrum of energy deposition events that represented the response function of the TEPC. The shape of each Geant4 spectrum was dependent on the range cut for electrons. By reducing the range cut, we effectively shifted energy deposition to higher values for large impact parameters. These effects are illustrated in Figs. 5 and 7. Although the visual appearance of the response function changed, there was little difference in the resulting estimates of the dosimetric quantities $\bar{y}_f$ and $\bar{y}_d$ (see Tables 2 and 3).

In summary, the Geant4 toolkit is capable of simulating energy deposition patterns in a spherical TEPC. It reproduces the stochastic nature of energy deposition in small volumes of tissue with dimensions that are similar to those of a mammalian cell. It has the flexibility to include large density variations, which are inherent in gas-filled dosimeters. Fine details can be reproduced when necessary by reducing the range cut to values $<10 \mu\text{m}$. This does, however, increase the computational time required to complete each simulation. The Geant4 toolkit can easily be adapted to simulate other geometrical configurations. The methodology described here did not include variations in the transposition from energy deposition into measurable electronic signals. However, averaged quantities used for dosimetry were faithfully reproduced.

Acknowledgments

The authors are grateful to Lionel Santibañez and Kathryn B. Carnes for their assistance in preparing this manuscript. Thomas Borak was supported, in part, by a NASA grant funded through the National Space Biomedical Research Institute (NSBRI).

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Fig. 1.

Schematic diagram of the experimental arrangement showing the position of the TEPC relative to the four pairs of position-sensitive silicon detectors (denoted as PSD1–PSD4) and of the 3-mm-thick lithium-drifted silicon detector (labeled as “3 mm”).

Fig. 2. Illustration of the transport of one incident particle (blue line) traveling from the left through the Geant4 simulated TEPC. The wall of the simulated TEPC is shown in grey. Secondary particle tracks are shown for negatively charged particles (red) and neutral particles (green). The tracks are projected onto the medial plane. Interaction points are also shown (white dots). This particle traveled through the diameter of the gas cavity, where impact parameter = 0.

Fig. 3. Response function in terms of energy deposited in the gas cavity, ϵ , for ^{56}Fe at 360 MeV/nucleon for particles with impact parameter, b , < 0.5 mm for the measured data (Gersey et al., 2002) and for the Geant4 simulated data.

Fig. 4. Mean energy deposited in the gas cavity, ε , vs. impact parameter, b , based on $LET \cdot dx$ alone, measured data (Gersey et al., 2002), and 2500 events simulated using Geant4 with a range cut for electrons of 1 μm . Data shown are for ^{56}Fe at 360 MeV/nucleon.

Fig. 5. Mean energy deposition, ε , vs. impact parameter, b , for the Geant4 simulated TEPC data for ^{56}Fe at 360 MeV/nucleon. Simulations were performed for three range cuts for electrons of 1 μm , 10 μm , and 100 μm .

Fig. 6.

Illustration of the transport of one incident particle (blue line) traveling from the left through the Geant4 simulated TEPC. The wall of the simulated TEPC is shown in grey. Secondary particle tracks are shown for negatively charged particles (red) and neutral particles (green). The tracks are projected onto the medial plane. Interaction points are also shown (white dots). This particle traveled through the gas-wall interface, where impact parameter, b , was 6.35 mm. The tracks were saved in a HEPREP file and plotted using WIRED3.

Fig. 7.

The response functions of the TEPC in terms of energy deposited in the gas cavity, ε , for ^{56}Fe at 360 MeV/nucleon for the measured data and for the Geant4 simulated data with range cuts for electrons of 100 μm , 10 μm , and 1 μm .

Table 1

Mean energy deposited in the gas cavity for particles with impact parameter <0.5 mm. Measured data are taken from Gersey et al. (2002).

⁵⁶ Fe beam energy (MeV/nucleon)	LET (keV/μm)	Mean energy deposited (keV)	
		Measured data	Geant4 simulated data
200	302	254	254
360	214	173	170
540	179	136	138
700	163	127	124
790	157	117	120
1000	149	116	112

Table 2

Frequency mean lineal energy, $\overline{y_f}$, and dose mean lineal energy, $\overline{y_d}$, for ^{56}Fe at 360 MeV/nucleon, with several varying range cuts for electrons. Measured data are taken from Gersey et al. (2002).

Method	Range cut (μm)	$\overline{y_f}$ (keV/ μm)	$\overline{y_d}$ (keV/ μm)
Measured data		184	224
Geant4 simulation	100	171	216
Geant4 simulation	10	179	222
Geant4 simulation	1	185	231
Geant4 simulation	0.5	187	233

Table 3

Frequency mean lineal energy, $\bar{y}_F$ and dose mean lineal energy, $\bar{y}_d$, for particles of all impact parameters (i.e., uniform beam). Measured data are taken from Gersey et al. (2002) and Taddei et al. (2006). Geant4 simulated data had a range cut for electrons of 100 μm .

Particle type	Energy (MeV/nucleon)	Velocity (β)	(ke V/ μ m)				
			Measured data		Geant4 simulation		
			y_F^-	y_d^-	y_F^-	y_d^-	
^4He	230	0.60	1.68	1.56	2.58	1.63	2.59
^{12}C	390	0.71	11.2	9.93	12.4	9.40	11.5
^{12}C	220	0.59	15.6	13.4	16.1	14.5	16.6
^{16}O	390	0.71	19.9	17.9	20.8	16.5	20.1
^{28}Si	380	0.70	61.9	50.4	59.8	49.4	60.9
^{56}Fe	1000	0.87	149	106	147	100	142
^{56}Fe	360	0.69	214	184	224	171	216