DEMONSTRATION OF A TIME-INTEGRATING MICRODOSIMETER

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ABSTRACT: A tissue-equivalent spherical proportional counter is used with a modified amplifier system to measure specific energy deposited from a uniform radiation field for short periods of time (on the order of microseconds to milliseconds) in order to extrapolate to dose in sub-micron tissue volumes. The signal is integrated over a variable collection time which is adjusted with a square-wave pulse. Charge from partical passages is collected on the anode during the period in which the integrator is triggered, and the signal decays quickly to zero after the integrator feedback switch resets; the process repeats for every "triggering" pulse. Measurements of energy deposited from x rays are examined. Spectral characteristics as a function of charge collection time are observed and frequency plots of specific energy and collection time-interval are presented.

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INTRODUCTION

Despite the numerous studies conducted which investigate the spatial deposition of energy from ionizing radiation in microscopic volumes [1-5], no experimental studies have been found which take into account the deposition of energy in both the spatial and temporal domains. Typically, microdosimetric studies explore the energy deposition characteristics of single particles, while few studies examine energy deposition resulting from incident radiation fields or fluxes. Indeed, simulations have been written to determine the space and time evolution of ionization in matter.[6] Yet experimental evidence of energy deposition over short and varying time periods is lacking. There is a need, therefore, to gain an understanding of energy deposition in space and time by measuring energy deposition frequency distributions as a function of charge collection time, $f(z,\Delta t)$. This understanding will help to create a correlation between the initial and subsequent energy deposition from radiation in a cell and the fast repair kinetics of the cell.[7] This may be understood by simulating tissue-equivalent spherical volumes down to diameters of 1 μm for collection times equivalent to the times necessary for biochemical repair of radiation damage. This paper reports on methods used to examine microdosimetric parameters as a function of time utilizing a microscopic gas-filled proportional counter and a gated signal. Distributions of energy deposition in a uniform field of x-rays, as opposed to fluxes of single particle, have been collected as a means of demonstrating the technique.

APPROACH AND METHODS

The primary goal of this research was to develop a microdosimetric system that can be used to measure energy deposition distributions (microscopic dose distribution) is sub-cellular, tissue-equivalent volumes as a function of time. In this work, these distributions were measured using a commercially available microdosimeter, standard counting electronics, and an integrating circuit developed in our laboratory. With this system, spectra of microscopic energy deposition characteristics during short time intervals can be analyzed for various radiation types. Timing intervals, during which energy deposition was recorded, were established using a digital gate such

that the charge collection could be toggled on and off with high precision. Energy deposition spectra are recorded for charge collection times ranging from 1 μs to 5 ms.

Because measurements are conducted in a uniform energy field, it is quite possible, and expected in many cases, for multiple particles to deposit energy in the detector during the longer charge collection times. Therefore, contrary to typical microdosimetric techniques, total energy deposited from multiple events will be collected rather than from individual events from the passage of single particles.

EQUIPMENT

Microdosimeter

The detector used is the LET-1/2 spherical tissue equivalent proportional counter.[1][8] The detector consists of a tissue-equivalent (TE) plastic sphere housed in a grounded aluminum shell. The shell serves as a vacuum tight housing, also making the detector submersible. The active volume is defined by a Shonka Type A-150 tissue-equivalent plastic sphere of thickness 0.127 cm and an inside diameter of 1.27 cm. The density thickness of the plastic sphere is calculated to be 142 mg/cm^2. The anode of the spherical detection volume is surrounded by a helix held at a slightly lower potential to create a more uniform electric field in the proportional region of the detector. This detector can be provided with or without an internal (alpha) calibration source. The one used here did not have the internal source.

Signal Integrator

The heart of the signal collection system is the signal integrator. The device acts as a continuous summing circuit for all detector signals. The integrator unit consists of two primary parts, the feedback amplifier which is the actual integrating device, and the timing logic circuits. These will be discussed separately, and an explanation of their concurrent function will follow.

The core of the feedback amplifier circuit is an ACF2101 Dual Switched Integrator Chip

[1]Far West Technology, Inc., 330D South Kellogg, Goleta, CA 93017.

(BP model, DIP) and is shown in Figure 1. This is a 24 pin integrated circuit produced by Burr-Brown.[1] The precise function of this chip (low charge transfer, low drift, low noise, and high speed) makes it ideal as a signal integrator. The input signal is fed into the inverting input of the circuit (pin 6). Integration takes place during the period of time in which the *reset* switch (pin 21) is in the open position. The *hold* and *select* switches (pins 20 and 22) can also be used to control the output signal. Switches are activated through TTL signals. In addition, the switches operate on an "inverse logic" basis. That is, a switch is open during logic high and closed during logic low. The chip operates at -12V and +5V.

The switching time is the time necessary for a switch to completely change state. For all switches in this circuit, this time is 200 ns. This value places a limit on the speed with which the chip is capable of operating. It is impossible to operate the device for integration times less than the switching time, as the switch will not change state rapidly enough. Rather, the minimum integration time must be greater than twice the switching time to allow for a complete change of state for the falling edge and the rising edge of the triggering signal.

The timing circuit to drive the signal integrator switches is shown in Figure 2. It consists of three bi-stable monovibrators (one-shots) constructed from timer ICs. The voltage converter in the circuit is placed such that the device can be operated from a NIM power module. Triggering of the circuit is done through the use of a TTL square wave provided by an external function generator. The *select* and *hold* signals are directly triggered by the input square wave, while the *reset* signal is triggered by the inverse of the *select* signal. The values of the components in the circuit are listed in Table 1.

The combined circuit, including the timing and integration circuits, was mounted to perf-board and encased in a steel housing. Four connections, in addition to the power connections, were made with BNC jacks. These connections include the input, the integrated output, the trigger, and hold signals. The width of the integration cycle is easily determined by examining the state of the hold signal with an oscilloscope. The basic circuit layout is shown in Figure 3. In addition to the

[1] 6730 S. Tucson Blvd., Tucson, AZ 85706

signal, trigger, and hold connections, three power connections were made to the circuit and crimped to plugs so that power could be drawn from the same NIM bin being used to operate the amplifier and high voltage modules. The entire unit uses +12V, -12V, and ground connections in the NIM bin.

Testing of the circuit was done using a constant current source - in this case, a stable voltage source of 0.707 V through a 22 kΩ resistance. The input resistance of the integrator chip brings the total input impedance to 23.5 kΩ. This results in a current, i, of 30 μA. By setting the hold time (and hence, the integration time) to a specific value, the amplitude of the output pulse, which is expected to be a square pulse of width equal to 8 ms (the time lag between the select switch closing and the reset switch closing), is expected to be given by the following:

$$A = \frac{i \bullet \Delta t}{C_f} = \frac{i \bullet \Delta t}{100 x 10^{-12}} \qquad (1)$$

where Δ_t is the integration time, and C_f is the value of the feedback capacitance in the integrator. For example, an integration time of 5 μs is expected to result in an output pulse of 1.5 V. Experiment shows that this is the case. The linearity of the integration can also be tested by disabling the *hold* and *select* switches such that they always remains closed. In this instance, the integration time is the time during which the reset switch is open, and the output should resemble a ramp pulse which drops off at a rate equal to the maximum slew rate of the integrator op-amp. Using Equation 1 and the constant current source described, for an integration time set at 25 ms, the maximum amplitude of the triangle wave pulse is expected to be 7.5 V. Again, the measured value corresponds to the calculated value.

Counting System

NIM modules used for signal processing were manufactured by EG&G Ortec[1], and include a voltage bias supply (model 478), a pre-amplifier (model 142A), a primary linear amplifier (model

[1]EG&G Ortec, 100 Midland Rd., Oak Ridge, TN 37831.

571), a secondary linear amplifier (model 575), and an ADC card (model 916A) with *Maestro* software.

Incorporation of the integrator unit into the counting system requires little more equipment than what is found in a basic counting system (Fig. 7). Since the integrator operates only in the negative direction, a second amplifier is necessary for pulse inversion. In addition, a series resistor is placed between the first amplifier and the integrator so that the current falls within accepted values. The oscilloscope is necessary to read the hold signal so that the integration time can be determined. The first amplifier is placed in the system in order to eliminate the very long tail of the pre-amplifier. This tail is undesirable as it has a signal decay time of approximately 50 ms, which is much longer than most signal integration periods. This would have the effect of collecting only part of the total signal from an event which, although takes place during the integration time, results in a pre-amplifier signal that is not totally collected. By having a much shorter pulse, events which take place during the integration time interval can be totally collected, and the error resulting in collecting partial events is reduced. The output from the first amplifier, A(t), with respect to time t is a Gaussian shaped pulse of the approximate form:

$$A(t) = A_0 e^{-\left(\frac{t-t_0}{\tau}\right)} \tag{2}$$

where τ is the time constant physically corresponding to the rise and fall time of the shaped pulses, A_0 is the output amplitude, and t_0 is the pulse center in time. In this case, t is set to 500 ns, which is low enough so that any input to the integrator is fully summed for all integration times, unless the input occurs near a switching point, in which case it is only partially integrated. This is expected, however, as the signal pulse train is of arbitrary frequency with time. It is seen that integration of Equation 2 results in a pulse whose amplitude is only dependent on A_0, again a desirable affect. It is also noted that the 571 amplifier has a minimum shaping time of 500 ns. This has the effect of returning an output pulse signal with a width no less than about 1 μs. Therefore, a lower limit of the integration time is enforced using this counting system. In order to decrease the integration

time, either a fast amplifier would be used, or the counting system would need to be modified such that the integrator collected anode charge as a charge sensitive amplifier.

INTERACTION CHARACTERISTICS AND CALIBRATION

It is possible that particles interacting in the detector gas outside the active volume may generate unwanted electrons in the active volume, thus generating unwanted signal (dose). For an ideal detector, the Bragg-Gray principle must be satisfied. That is, the detector's active volume must be small compared to the range of secondary charged particles produced in the medium so that the particle flux is not greatly affected. In addition, the surrounding medium must be large compared to the range of secondary charged particles so that electronic equilibrium is established.[9]

In the case of Compton scattered electrons that enter the active volume from photon interactions in the aluminum wall, the maximum electron energy occurs from backscattered photons.[9] For 250 kVp x-ray photons, the maximum energy of a recoil electron is calculated to be 0.124 MeV. Since the range of electrons in matter depends only slightly on the material,[9] a general value can be obtained for the range of electrons scattered from x rays, using:

$$R = 412E^{(1.265-0.0954\ln E)} \tag{3}$$

where R is the range in mg/cm^2 and E is the electron energy in MeV.[10] Electrons with energy of 0.124 MeV, therefore, have an approximate range of 19.4 mg/cm^2. Thus, Compton electrons produced outside the tissue equivalent sphere do not penetrate the A-150 plastic to reach the active volume.

The second condition requires the thickness of the surrounding medium to be larger than the range of the secondary electrons, so that electronic equilibrium is established. The surrounding medium is taken to be the plastic sphere surrounding the active volume and the fill gas between the wall and the aluminum housing. Since the gas-filled region between the aluminum housing and the plastic wall is 0.270 cm thick, and since the detector is operated at a gas pressure of 58.75 torr (to be discussed below), then the density thickness of this region is calculated to be 0.22 mg/cm^2,

negligible in comparison to the plastic wall's density thickness of 142 mg/cm^2. Compton scattered electrons of 0.124 MeV have a range of 19.4 mg/cm^2, much less than the thickness of the plastic shell. The plastic shell is quite important in maintaining electronic equilibrium for the 250 kVp x rays used in this demonstration.

Detector Calibration

A method of calibration using a neutron source is employed.[11] It is assumed that recoil protons produced by neutron interactions in the gas have a roughly constant LET as they traverse the detector active volume. The assumption is valid since the loss in energy over one micron of tissue is expected to be only a small fraction of the total proton energy, and the LET of the recoil proton does not drop significantly with a change in energy. Therefore, the maximum energy deposited by these protons is equal to the product of the maximum LET of the protons and the largest chord length of the detector, in this case, the diameter of the active volume.

The maximum stopping power of recoil protons in the cavity is calculated as:

$$S_{\max} = \frac{8\pi z^2 N_0 Z \rho}{e^1 I A} \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \qquad (4)$$

Using this relation and values of Z, A, r, and I corresponding to our tissue equivalent gas at a pressure of 58.75 torr (to simulate a 1 μm diameter tissue sphere),[11] the maximum deposition energy of recoil protons produced in the detector sphere is calculated to be 108.4 keV per traversal of the detector diameter, and this is the energy of the "proton edge" in the energy spectrum.[11] Since there is very little matter in the detector volume (i.e., the simulated volume is quite small and gas pressure is low), then this value of LET can be assume to be constant across the diameter of the detector.

A calibration spectrum collected with the LET-1/2 detector is shown in Figure 4. The proton edge is quite apparent, as well as some heavy recoil counts. This calibration method works quite well for a typical microdosimetric spectroscopy system. However, calibration of the system

with an integrator inserted becomes more difficult as it becomes necessary to consider the fact that in order for the integrator to produce a finite signal, it must integrate over a period of time. Due to the stochastic nature of the events in the detector, the event frequency (and hence, the period between adjacent events) is random. To calibrate the system correctly, it is necessary to read only one event at a time. However, this is not necessarily true with the integrator inserted in the system. The situation is complicated by the fact that one does not necessarily know how many events are summed during the integration period. The problem was addressed using the following method.

Initially, the neutron spectrum in Figure 4 was taken with an ordinary counting system (i.e., without the integrator or second amplifier). An Ortec 480 pulse generator was used to generate an artificial signal of the same energy (same channel) as the neutron edge. A test pulse amplitude of 154 mV was sufficient to create a spike in the same channel as the proton edge of the neutron spectrum. This pulse was introduced into the complete counting system shown in Figure 5. The integration time was set to be equal to the input pulse period of 16.6 ms (since the pulse frequency was 60 Hz). A single event during the integration period is assured since the pulses are evenly spaced in time and only one pulse will occur during this time. This calibration spectrum is shown in Figure 6. The primary peak is the peak corresponding to an artificial pulse from the pre-amplifier equal to a pulse from a proton of maximum LET crossing the diameter of the detector's active volume. The smaller, secondary peak is the noise spectrum from charge transfer and line noise. This spectrum was produced simply by turning the pulse generator off. Therefore, the only output was the integration of noise in the spectrum. This method has the advantage of presenting an average value of noise in the spectrum.

The noise spectrum, expected to approximate a Gaussian distribution about an average value, is dealt with differently than an ordinary background spectrum. Since the signal pulses from the integrator are the sum of signal and noise, all pulses are expected to be offset by an average noise value. In addition, since this noise value is distributed about an average value, a peak in the spectrum will be the convolution of the noise spectrum and the original peak. This has the effect of making peaks wider, as is shown in the calibration peak in Figure 6. Since the integration period

was quite long and the calibration pulse of low amplitude, one expects a summed noise pulse to be similar in amplitude to the calibration pulse. In the case of the integration spectrum, the calibration peak, collected in channel number 565, is offset by the average value of the noise, or 306 channels, so the actual value of the calibration peak is in channel number 259. This channel can be calibrated to an energy value of 108.4 keV, and a specific energy value of 32.6 Gy, calculated by taking the quotient of the energy deposited and the mass of the simulated tissue sphere.

This calibration method has the advantage that the linearity of the system can be easily checked by adjusting the amplitude of the input pulse. Using the previous input pulse producing a peak at channel number 565 (with noise integrated into the signal), if its amplitude is reduced by a factor of 2, then the channel number in which the peak is expected to occur would be the channel of the net peak divided by 2 and added to the noise offset of the system. Therefore, a pulse of one-half of the original amplitude is expected to be in channel number 436 with an error equal to the FWHM of the calibration peak. The actual peak fell quite close to channel number 436, well within the error value, so the MCA was taken to be linear with input energy. The linearity of the system becomes evident later as spectra are examined and discussed.

For spectra collected with an inverting amplifier gain of 10 and a primary amplifier gain of 250, the conversion factor from channel number to specific energy for a 32 bit MCA was 0.128 Gy/channel.

DATA COLLECTION

Using the experimental setup and equipment described, energy deposition spectra were collected for various integration times. The times for which data were collected included 1, 10, 50, 100, and 500 μs as well as 1, 2, and 5 ms. For each collection sequence corresponding to a specific integration time, the MCA count, integration time, and the corresponding duty cycle were recorded. Counting times for the 250 kVp x-ray source (50 mA) were consistently 180 s. In order to set the integration time properly, an oscilloscope was coupled to the *hold* connection on the integration circuit. In order to avoid saturation of the solid state switches in the integration circuit, power was

turned on before the triggering signal was connected. After powering up the circuit, the square wave trigger signal was applied to the *trigger* input and was adjusted until the width of the *hold* signal was equal to the desired integration period. It was not necessary to provide an input signal to the integration circuit during the reading of the *hold* signal as this is not affected by an input signal, nor was it necessary to provide power to the detector or the pre-amp.

The integrator chip, being very sensitive to minute changes in charge across the switches was encased in a steel housing with a wall thickness of 0.32 cm. The housing was also shielded with lead bricks.

The amplifier signal was connected in series with the input resistor to the integration circuit. Having set the integration cycle, the detector power was turned on, and spectra were collected. For all spectra collected, the gain on the first amplifier was held at 250. For most spectra, the gain on the inverting amplifier was held at 10. In cases where dose rate was large, the integrator chip saturated at higher integration times; therefore, the inverting amplifier gain was reduced. In some instances, the gain was increased due to the small amount of charge collected during short integration times. Since the system was calibrated to a gain of 10, all spectra collected were normalized to a gain of 10 before conversion to energy values. For all integration times, noise spectra were collected. These spectra were used to determine the offset in the signal spectra using the method outlined previously. All energy spectra were placed into an MCA spectrum of 32 bit resolution (1024 channels).

DATA ANALYSIS

Spectral analysis was accomplished first by converting the spectral data to a text tabular format using the *chconv* routine in the *Maestro* software package[1]. The file was then analyzed using *Lotus 1-2-3* (release 5)[2]. Any positive offsets in the spectra were then subtracted. The horizontal axes of the spectra were converted to specific energy in units of Gy first multiplying by the quotient of 10 and the gain of the inverting amplifier (to obtain spectra all normalized to the same energy values) and then multiplying the resulting values on the horizontal axis by the

[1]EG&G Ortec Software.
[2]Lotus Development Corporation, Mountain View, CA.

calibration factor (such that channel 259 corresponds to 32.6 Gy). Since system noise, which would otherwise be discriminated against in typical counting systems, was actually integrated into the signal, a positive offset resulted in the spectra. This offset was accounted for by determining its magnitude through collection of a noise spectrum. For larger integration times, the signal noise offset peak did not appear in the signal spectrum. This is due to the fact that the output of the integrator was a single pulse whose amplitude corresponded to the sum of the signal pulse and any noise occurring during the integration period, which was large enough such that the probability of at least one actual event occurring in the detector was large. Therefore, the spectrum would appear without the noise pulse, because all events would be the sum of at least one signal pulse and the system noise. However, as the integration period decreases, the probability of an event occurring during the integration period decreases, and many output pulses from the integrator are only the sum of noise pulses, creating a low energy contribution to the spectrum. In the case where the signal spectrum overlapped the noise spectrum, the noise peak in the noise spectrum was also evident as a peak in the signal spectrum. This was easily identified, as one expects the signal spectrum to be a distribution of energies about an average value.

Spectra were converted to the standard form of $z^2f(z)$ as a function of log(z). In addition, spectra were converted to the dose distribution zf(z) as a function of log(z) for comparison. The frequency average dose was also calculated and plotted as a function of integration time.

Though three different distributions are prepared, the one of choice is $z^2f(z)$ as a function of log(z).[11] This not only brings an added convenience of production of a spectrum that is easier to interpret, but the properties of the dose distribution are maintained through a simple relationship. Since the total frequency average dose deposited by a source is given by:

$$z_F = \int_0^\infty zf(z)dz \tag{5}$$

then the dose contribution from a particular specific energy, z, is given by:

$$d(z) = \frac{zf(z)}{z_F} \tag{6}$$

so that the contribution to dose from specific energies between z_1 and z_2 can be related by:

$$\int_{z_1}^{z_2} d(z)dz = \frac{1}{z_F}\int_{z_1}^{z_2} zf(z)dz = \frac{1}{z_F}\int_{z_1}^{z_2} z^2 f(z)dz\log(z) \tag{7}$$

RESULTS AND DISCUSSION

Although a wide range of effects will influence the spectra, particularly in the microdosimetric domain, a collected spectrum is expected to be a convolution of the energy deposition spectrum and the effects that a detection system will have on a monoenergetic source. Since the x-ray source emitted a continuous spectrum of energies, then the relative variance in the spectra were expected to be larger.

The standard microdosimetric energy deposition spectra for integration times of 500 μs and higher are shown in Figure 7. These spectra follow a Gaussian distribution, with the average dose contribution increasing with integration time. Quite noticeable is the extremely high peak from the spectrum obtained with an integration time of 5 ms. Since the peak height increases by a factor of z^2 (note y axis), one certainly expects the 5 ms peak to be the highest. However, other contributions to this height include the lack of lower energy events in this peak. As the integration time decreases, the average number of events during an integration period decreases. With fewer events, the signal pulses are of lower amplitude and a larger number of lower energy events are averaged into the mean dose. If many events are clustered about zero, on a plot which increases as z^2, the zero energy events will not be as visible.

The dose spectra for lower integration times are displayed in Figure 8. Since the average dose contribution decreases with integration time, the noise contribution is minimal in these spectra. The low energy contribution evident in Figure 8 is expected to be from the integration periods

during which no event occurs. As the integration time decreases, the probability of an event occurring during the integration period also decreases. However, noise is always integrated into the pulse, so the low energy "events" occur. As the integration period decreases further, the noise contribution is lower and drops below the detection limit of the spectroscopy system.

It is seen that the spectra for integration times are very similar to a single-event spectrum as the integration time approaches 1 μs. This is expected since the integration time period approaches the width of a signal pulse. That is, a maximum of one signal pulse can be collected by the integrator during this period. Secondly, as the integration time period decreases, the probability of multiple-pulse collection also decreases, so that it becomes quite improbable that two or more signal pulses are collected during a lower integration period.

The x-ray source dose-rate can best be analyzed by examination of a plot of the frequency average dose as a function of integration time. This plot is shown in Figure 9. The positive y-intercept shows that the function has a slight offset. This offset is believed to be due to a combination of a higher average dose at lower energies due to the finite detection limit of the MCA, eliminating very low energy events from the spectrum; charge and noise transfer in the integrator; as well as slight defects in the baseline (zero) restoration of the system causing a slight positive offset. Likewise, if it is assumed that events are integrated whole, that is, only an integral number of events are integrated in the spectrum, then the lowest possible energy integrated would be that due to a single event. Therefore, the lowest possible finite energy value in the spectrum would be the average energy deposited by one event, and this could also explain the offset in the plot. The plot is also very linear, with an R^2 fit of 0.994. As well, the slope of this plot corresponds to the dose rate of the source in the microscopic volume of interest. For this type of measurement, comparison of slopes would not only be a good indicator of dose rate, but also a tool for comparison of the effectiveness of various sources.

Table 2 gives a listing of absolute and relative variances for the frequency average doses from the x-ray source. The absolute variance is taken to be the half-width at half-maximum (HWHM) of the spectral peak. Many uncertainties have been discussed in the past concerning the

variance in the spectral peak,[11] and the x-ray spectrum seems to have a higher absolute variance than others taken with the same method. This would most likely be attributed to the broad spectrum of x-ray energies incident on the detector causing a broader range of secondary electron energies.

For this x ray source, the absolute variance increases with integration time. This is expected as a broader range of integrated noise is possible, and the width of the noise spectrum increases with time. However, the relative variance seems to increase to an asymptotic level. One expects the absolute variance to be constant as this is determined by the peak width, which is determined by the signal and event processing system, however, since the low energy spectra are not complete Gaussian distributions (i.e., there is no low energy tail because most events are clustered around zero), the HWHM of the distribution is distorted, giving a value lower than expected, and, hence, a lower variance.

CONCLUSIONS

We have developed a microdosimetric counting system that allows the collection of energy deposition spectra as a function of time. The system was demonstrated using 250 kVp x rays (50 mA) and charge collection times ranging from 1 μs to 5 ms. The integrating circuit and the data collection and analysis methods have been described in detail. Calibration was carried out utilizing calculated maximum LET values for recoil protons generated by neutron interactions in a tissue-equivalent medium. A method for removing electronic noise from energy deposition spectra was presented. As expected, frequency average dose (macroscopic dose) is linear with integration time. Data generated with this system can be used to determine the severity of effect in organisms exposed to various radiation sources. These biological applications are described elsewhere.[12]

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FIGURE CAPTIONS

Figure 1. ACF2101 Schematic and Pinout.

Figure 2. TTL Timing Circuit for Signal Integrator.

Figure 3. Basic Circuit Diagram of Timing and Integration Unit.

Figure 4. Neutron Calibration Spectrum for LET-1/2 Counter.

Figure 5. Experimental Setup for Signal Collection.

Figure 6. Calibration Spectrum for LET-1/2 Signal Integration System.

Figure 7. X-Ray Dose Spectra for Various Integration Times.

Figure 8. X-Ray Dose Spectra for Integration Times Less than 0.5 ms.

Figure 9. Frequency Average Dose as a Function of Integration Time for 250 kVp X Rays

Table 1. Component Values for the TTL Timing Circuit

Component	Value	Units
R_S	10	Ω
R_H	1	MΩ
R_R	100	kΩ
C_S	22	nf
C_H	22	nf
C_R	22	nf
C_{OUT}	22	nf
R_{OUT}	2.2	kΩ

Table 2. Variance and Relative Variance of Dose Distributions vs. Integration Times for 250 kVp X Rays.

t_{int}	σ (Gy)	V
5 ms	2.717	0.891
2 ms	1.817	1.009
1 ms	1.105	0.519
0.5 ms	0.186	0.021
100 μs	0.056	0.003
50 μs	0.04	0.002
10 μs	0.018	0.004
1 μs	0.012	0.002