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FURTHER DEVELOPMENT OF THE VARIANCE-COVARIANCE METHOD

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Abstract — Applications of the variance-covariance technique are presented that illustrate the potential of the method. The dose mean lineal energy, $\bar{y}_D$, can be determined in time-varying radiation fields where the fluctuations of the dose rate are substantially in excess of the stochastic fluctuations of the energy imparted. An added advantage is, that $\bar{y}_D$ is little influenced by noise that affects both detectors simultaneously. The variance-covariance method is thus stable with respect to dose rate fluctuations and other temporal variations of a radiation field, and to various influences of noise and electronic artefacts. The dose mean lineal energy obtained at different simulated diameters agrees well with experimental data by other authors and can be determined for small simulated diameters (below 100 nm).

INTRODUCTION

In radiation fields of fluctuating intensity the dose mean energy imparted, $\bar{\epsilon}_D$, specific energy, $\bar{z}_D$, or lineal energy, $\bar{y}_D$, may be determined by the variance-covariance method[1]. A pair of detectors (the twin detector) is exposed to the radiation field and registers the energies imparted within each of the detectors simultaneously. From the paired values for a series of sampling intervals one can determine the variance of the signals of each detector and the covariance between the signals of the two detectors. The variance reflects all fluctuations of energy imparted, the covariance only the dose rate fluctuations; their difference corresponds, therefore, to the intrinsic microdosimetric fluctuations which are a measure of radiation quality. There have been several recent approaches, to developing the variance-covariance technique as a system for radiation protection measurements[2-4]. Some further developments will here be reported.

MATERIALS AND METHODS

A pair of tissue-equivalent cylindrical proportional counters (outer diameter, 44 mm; inner diameter, 20 mm; effective electrode length, 20 mm) with methane based tissue-equivalent gas was employed to perform measurements in a field of constant and varying dose rate; a 185 MBq ^{137}Cs source was utilised. The identical detectors have guard electrodes to define the length of the sensitive volume and to prevent leakage currents from reaching the collecting electrode. The detector currents were measured by electrometers which were used as current integrators. Details of the electronic signal processing system have been described earlier[4]. Calibration of the proportional counters was performed with a ^{241}Am α source. The energy spectrum and the LET spectrum in tissue-equivalent gas were determined for the collimated beam by a semiconductor detector. The gas multiplication factors for different gas pressures and electrode voltages were then evaluated.

Individual sampling series in the measurements contain up to N=10,000 data pairs (from N sampling intervals). A sampling series can be obtained within one charge integrating process, or, in order to improve resolution, it can be subdivided into several sampling cycles, each of them covering the dynamic range of the charge accumulating device. From the N data pairs for each detector the mean, $\bar{\epsilon}$, of the energy imparted, its relative variance, V, and its relative covariance, C, are determined. The dose mean energy imparted per energy deposition event is[1]:

$$\bar{\epsilon}_D = (V-C)\cdot\bar{\epsilon} \tag{1}$$

where the quantities $\bar{\epsilon}$ and V and the corresponding value $\bar{\epsilon}_D$ can refer to each of the detectors.

The corresponding values of the specific energy, $\bar{z}_D$, and the lineal energy, $\bar{y}_D$, are:

$$\bar{z}_D = \bar{\epsilon}_D/m \text{ and } \bar{y}_D = \bar{\epsilon}_D/\bar{l} \tag{2}$$

where m is the mass of the simulated sensitive volume; $\bar{l}$ is the mean chord length, which in the following is termed the 'simulated diameter' of the detectors.

RESULTS AND DISCUSSION

Compensation of noise

Signal noise, offset currents, and other electronic artefacts lead to an increased variance of the signals. To examine the influence of noise on the derived dose average event sizes, a varying degree of noise, affecting both detectors simultaneously in phase, was superimposed on their signals. The term 'noise' stands, in this context, for the root mean square (rms) of any spurious contribution to the signal.

Figure 1 shows the derived values of the dose mean lineal energy, $\bar{y}_D$, obtained in the constant radiation field with specified rms values of the superimposed noise. Omission of the covariance term, i.e. simple employment of the variance method, leads to unusable values of $\bar{y}_D$ (Figure 1, top panel). The influence of the noise on the measured values is, however, substantially reduced by inclusion of the covariance term. In the intermediate panel of Figure 1 the values of $\bar{y}_D$ are shown which result from the same data set when the variance-covariance method is applied. With increasing rms values of the noise one finds, even with the variance-covariance method, an increase of $\bar{y}_D$ for one detector, whereas in the other detector a decrease is obtained. The difference between the two detectors is due to the fact that they were subject to slightly different dose rates and, possibly, due to slight inaccuracies of the calibrations of the two channels. If exactly the same doses were measured in both detectors, and if the noise were equal and in phase for both detectors, there should be no bias due to the noise, i.e. the values of $\bar{y}_D$ would remain unaffected in the variance-covariance method. Noting the different ordinate scales in Figure 1, one observes that the deviations are considerably smaller than those that are obtained with the variance method. The errors are, nevertheless, unacceptable at high noise levels, but they can be effectively eliminated by utilisation of the average of $\bar{y}_D$ for the two detectors.

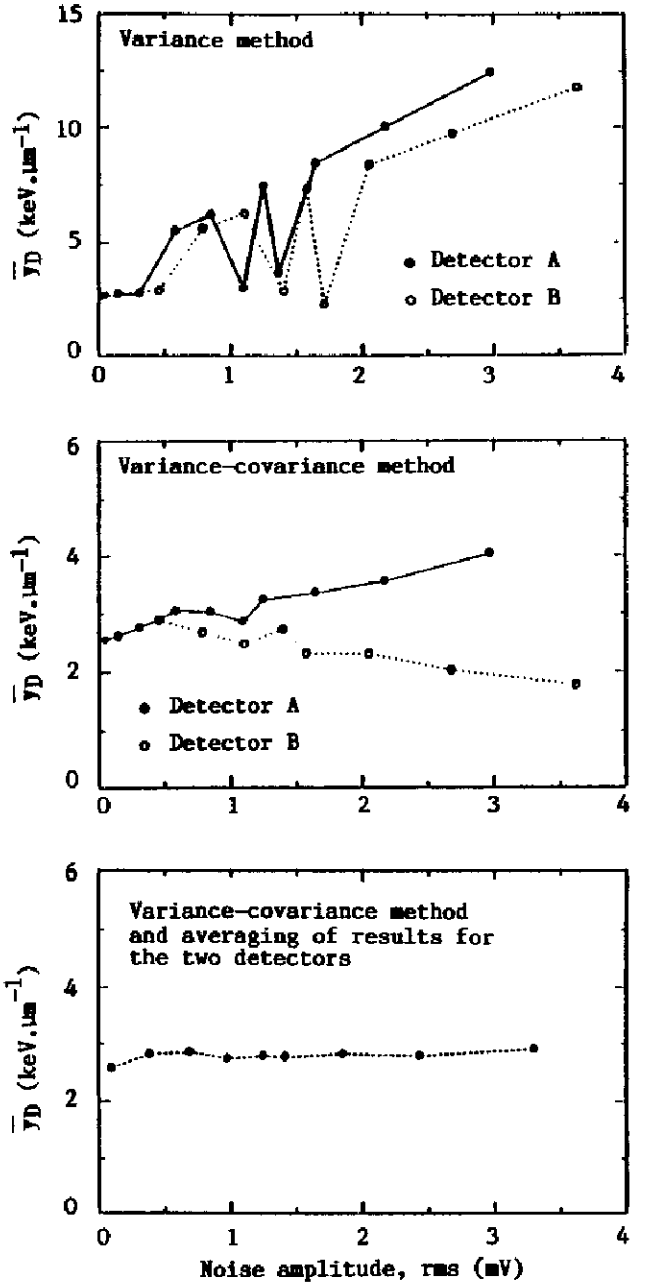

Figure 1. Dose mean lineal energy, $\bar{y}_D$, determined in a constant ^{137}Cs radiation field with superimposed noise of different root mean square (rms). The evaluation is performed according to the Variance Method (top panel), the Variance-Covariance Method (intermediate panel), and the Variance-Covariance Method with averaging the values $\bar{y}_{D,A}$ and $\bar{y}_{D,B}$ from detectors A and B (bottom panel). Note the different ordinate scales.

$$\bar{y}_D = (\bar{y}_{D,A} + \bar{y}_{D,B})/2 \qquad (3)$$

An almost constant value of $\bar{y}_D$ is then obtained over the total range of noise rms (about 2 orders of magnitude) (Figure 1 bottom panel). The variance-covariance method is thus able to compensate for superimposed noise, if it affects both detectors simultaneously, i.e. if it is correlated.

Time-varying radiation field

Employing the variance-covariance technique one can determine the lineal energy, $\bar{y}_D$, even in the presence of dose rate fluctuations and, generally, in time-varying fields. Figure 2(b) shows the values of $\bar{y}_D$ obtained in the field of the ^{137}Cs source; the different degree of temporal variations is expressed in terms of C/(V–C), i.e. the ratio of the relative variance of the dose rate to that of the actual microdosimetric fluctuations per sampling interval. For C=0 the dose rate variations vanish and the radiation field is constant; for C/(V–C)=10 the dose rate fluctuations contribute about 91% to the total variance. As can be seen from Figure 2(b), the derived values of the lineal energy, $\bar{y}_D$, are sufficiently constant over this range of dose rate variations. Figure 2(a) gives an example of the time course of the energies imparted, ϵ_i, in a series of N=150 sampling intervals, each of duration 0.2 s.

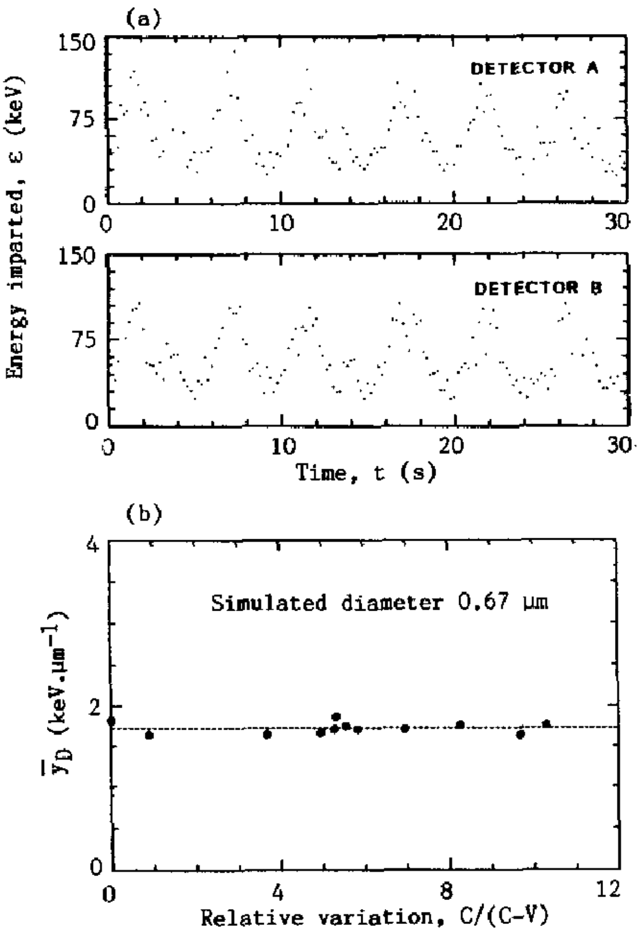

Figure 2. (a) Successive values of energy imparted, ϵ_i, per sampling interval for detector A and B in a time-varying field with C/(V–C)=6. The duration of each sampling interval is 0.2 s, and the sampling series contains 150 data pairs. (b) Dose mean lineal energy, $\bar{y}_D$, in the time-varying radiation field for different ratios, C/(V–C), of the dose rate variations to the stochastic variations of energy imparted.

The diagram illustrates the large predominance of the dose rate fluctuations in the case C/(V–C)=6.

Dependence of lineal energy on site size

The quantity $\bar{y}_D$ was determined in the constant

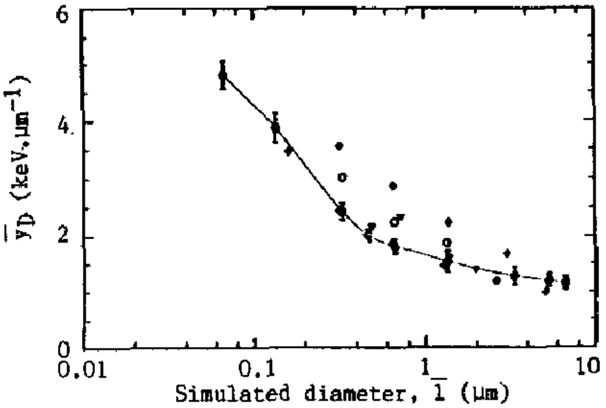

Figure 3. Dose mean lineal energy, $\bar{y}_D$, determined in a constant field of ^{137}Cs γ rays for different simulated diameters, $\bar{l}$, by the Variance-Covariance Method (solid circles), and comparison to experimental data obtained by other authors. Key: (◆) Coppola *et al* 1976[5], (○) Varma *et al* 1981[6], (▼) Haque and Saq'an 1978[8], (◇) Dvorak 1975[7].

field for various simulated diameters, $\bar{l}$, or the sensitive volume. At all simulated diameters except the lowest ones $\bar{y}_D$ was measured with different gas multiplications; the range of sufficient gas multiplication is narrow for small simulated diameters, and the data for $\bar{l}$ = 67 nm and 133 nm were therefore taken at a single gas multiplication. Figure 3 shows the results for simulated diameters between 67 nm and 6.7 μm, and compares them with data obtained earlier by other authors with different experimental techniques[5-8]. Our results agree best with the data obtained by Dvorak[7]. There are systematic differences up to 50% among the other data. The variance-covariance technique permits, in principle, the determination of $\bar{y}_D$ for simulated diameters down to some ten nanometres. Similar measurements by the conventional single-event pulse-height technique are impracticable, at least in pulsed fields, because of the excessive measuring times that are then required for sufficient statistical precision.

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