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DETERMINATIONS OF THE DOSE MEAN OF SPECIFIC ENERGY FOR CONVENTIONAL X-RAYS BY VARIANCE-MEASUREMENTS

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Abstract

The dose mean value (ζ) of specific energy of a single event distribution is related to the variance of a multiple event distribution in a simple way. It is thus possible to determine ζ from measurements in high dose rates through observations of the variations in the ionization current from for instance an ionization chamber, if other parameters contribute negligibly to the total variance. With this method it has earlier been possible to obtain results down to about 10 nm in a beam of ^{60}Co-γ rays, which is one order of magnitude smaller than the sizes obtainable with the traditional technique. This advantage together with the suggestion that ζ could be an important parameter in radiobiology make further studies of the applications of the technique motivated.

So far only data from measurements in beams of a radioactive nuclide has been reported. This paper contains results from measurements in a highly stabilized X-ray beam. The preliminary analysis shows that the variance technique has given reasonable results for object sizes in the region of 0.08 μm to 20 μm (100 kV, 1.6 Al, HVL 0.14 mm Cu). The results were obtained with a proportional counter except for the larger object sizes, where an ionization chamber was used. The measurements were performed at dose rates between 1 Gy/h and 40 Gy/h.

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INTRODUCTION

Microdosimetry is concerned with the stocastic behaviour of energy depositions in usually tissue equivalent materials. Since Rossi's original work 1959 much effort has been put into the subject, both at theoretical and experimental level. Most of the work with low-LET radiation has been concentrated on ^{60}Co gamma rays but work with conventional x-rays has also been reported, see Booz (1976) for a review.

So far most work has been directed towards measurements of single event distributions of the energy deposited using the traditional pulse height analysis method which, however, with traditional proportional counters is limited to object sizes down to about 0.3 µm. If less information can be accepted it is possible with the so called variance technique (Bengtsson, 1970, 1972) to determine the dose mean of specific energy in a single event distribution for even smaller object sizes. This paper reports results from variance measurements in a highly stabilized beam of x-rays.

There are several reasons to do these measurements. A possible extension of the variance technique to beams with variance contributions, not related to energy straggling should be of general interest. Working in a standardizing laboratory, we are also interested in applications of microdosimetry to radiation dosimetry and are planning to make detailed parallel studies of both dosimetric and microdosimetric quantities. As an example the mean lineal energy has been reported to be inversely proportional to the logarithm of the exposure half value layer under certain conditions (Lindborg, 1978). The suggested use of the dose mean lineal energy value for calculation of quality factors in radiation protection (Rossi, 1977) could make the variance technique specially interesting in radiation protection. Finally many radiobiological studies are still made in beams of conventional x-rays and an extension of microdosimetric data towards smaller object sizes should be of interest.

THEORETICAL BACKGROUND

The specific energy, z, is defined as the energy imparted to a specified region by ionizing particles divided by the mass of that region. The energy imparted can be associated with one or more events and with the notation z_n here is meant the specific energy caused by exactly n events. If the number of events is large then $\bar{z}$ equals the mean absorbed dose, D, to the specified region. The dose dependent distribution $f(z; D)$ can be written as

$$f(z;D) = \sum_{n=0}^{\infty} e^{-m} \frac{m^n}{n!} f_n(z) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where $f_n(z)$ is the distribution of z when exactly n absorption events have occurred and $m = \bar{z}/\bar{z}_1$ is the mean number of events at D. The frequency mean ($\bar{z}_1$) and the dose mean (ζ) of the single event distribution, $f_1(z)$, is defined as

$$\bar{z}_1 = \int_0^{\infty} z f_1(z)\, dz \text{ and } \zeta = \int_0^{\infty} z^2 f_1(z)\, dz/\bar{z}_1$$

It has been shown (Bengtsson, 1970) that the relative variance (V_{rel}) of the distribution f(z; D) is given by

$$V_{rel} = \zeta/D \quad \text{.......................................} \quad (2)$$

Thus measurements of the relative variance, V_{rel}, at the absorbed dose, D, can be used for the determination of ζ, or the related quantity dose mean of the lineal energy $\bar{y}_D$.

EQUIPMENT

The x-ray equipment consists of two electrostatic generators (Tunzini Sames, type 140-14) and a 300 kV therapy tube with an inherent filtration of 1.8 mm Al. Both the high voltage and the anode current are stabilized through feedback systems. A test of the stability properties has been carried out (Forsberg, 1974) and for a potential of 100 kV a drift of less than $0.5 \cdot 10^{-4}$ per hour in voltage after an initial warming up period of an hour was reported. The short term relative fluctuations in the potential (seconds) were found to be less than 10^{-4} (1 SD). The corresponding variations for the anode current were found to be less than $0.5 \cdot 10^{-4}$ for currents between 0.15 mA and 13 mA.

The precise electrical current measurements, necessary for the determination of the variance, were made with an equipment described in detail by Samuelson, Bengtsson (1973). This unit enables repeated and precise measurements of the average electrical current through measurements of the time required to accumulate a given charge on a capacitor.

MEASUREMENTS

Two series of measurements were performed. The first with an ionization chamber with 3 mm thick walls of air equivalent plastic and with the ionization chamber placed in a vacuum tube with a 2 mm thick Al-wall. This serie of measurements was made for object sizes with diameters between 0.7 and 22 µm.

The second serie was made with a spherical proportional counter described by Lindborg (1974). The walls of the counter were made of tissue equivalent material (A 150) 3 mm thick, and with a 0.2 mm thick Al-cover. As the radiation beam was filtered with totally 3.4 mm Al the different thicknesses of the Al-covers in the two series would make the energy fluence spectrum slightly different. A continuous flow of methane based tissue equivalent gas was used here. With this technique objects with diameters in the range 0.04 to 7 µm were studied. The gas multiplication was determined for each object size and exposure rate used, and were made both with the collector negative respectively positive to the wall, to increase the accuracy of the current in the ionization chamber region. From the graph the current with no gain was determined. At the smallest object sizes the current with no gas multiplication was to weak to become measureable and the value was instead obtained from an extrapolation in a graph showing the ionization current as a function of the gas pressure, Fig. 1. In the proportional counter serie an exposure rate was chosen in such a way that the integration time always became about 5 s irrespective of the gas multiplication, which had to be increased at decreasing object size to keep the signal well above the noise level.

To get comparable results from the two series the results from the second one had to be normalized to the same primary charge as in the first serie. This was done according to

$$\sigma_{rel} = \sigma'_{rel,G} \left(Q'/Q\,\bar{G}\right)^{\frac{1}{2}} \quad \text{.............................} \quad (3)$$

where

$\bar{G}$ = gas gain

Q = mean integrated charge in the ionization measurement

Q' = mean integrated charge in the proportional counter measurement

$\sigma'_{rel,G}$ = relative measured standard deviation in the proportional counter measurement.

Due to the high stability of the exposure rate in the x-ray beam it was not necessary to use any monitoring system. A detailed discussion of the underlying reasons for this will be presented below.

For every simulated volume three series of measurements were performed each of which consisted of 50 values. With this number of measurements the estimated standard deviation predicted from statistical theory (Natrella, 1966) is about 12 % from its true value (95 % confidence level). The total uncertainty was estimated to be 25 per cent for volumes < 0.3 μm and 15 per cent for volumes > 0.3 μm.

With the same proportional counter and identical irradiation conditions but at reduced exposure rates pulse height measurements for a 1 μm simulated volume were performed. The single event distribution was only determined relative to that for a collimated ^{60}Co gamma ray source.

All the x-ray measurements were made at 100 kV and an added filter of 1.6 mm Al (HVL 0.14 mm Cu).

RESULTS

From the repeated measurements of the time a relative variance, V_r, was calculated and the dose mean value of the specific energy distribution, ζ (unit gray), was calculated according to the formula

$$\zeta = \frac{6\, V_{rel}\, Q\bar{W}}{\pi\, d^3\, \rho_o e}$$

where

Q is the mean value of the collected charge (C) for which V_{rel} is given, d is the sphere diameter (μm) and $\bar{W}/e$ is the mean energy expended per ion pair formed per electron charge (J/C), (33.7 J/C for air, 30 J/C for TE gas). ρ_o is the density of the gas in the chamber (kg/m^3).

The results are presented in Fig. 2 and 3, which give the relative standard deviation ($\sigma_r = \sqrt{V_{rel}}$) and the dose mean lineal energy ($\bar{y}_D$) respectively as a function of the simulated object diameter.

For the x-ray data, the relative standard deviation (σ_{rel} becomes approximately 1.5 above that for ^{60}Co gamma rays for all investigated object sizes.

The experimental results in Fig. 3 have been fitted to a curve giving the dose mean lineal energy $\bar{y}_{D,x}$ (keV/µm) as a function of the object size diameter. This curve becomes

$$\bar{y}_{D,x} = 4.19 \cdot d^{-0.36} \quad \text{correlation coefficient } r = 0.96$$

A comparison with values measured with walled proportional counters by Braby and Ellet (1971) shows that our data is about 13 per cent lower. This could be due to both experimental uncertainties as well as differences in radiation qualities.

For the ^{60}Co gamma rays data presented by Bengtsson and Lindborg (1974) also given in Fig. 3, the line can be written as

$$\bar{y}_{D,Co} = 2.01 \, d^{-0.40} \quad 0.01 \text{ µm} < d < 22 \text{ µm}$$

The ratio between $\bar{y}_{D,x}$ and $\bar{y}_{D,Co}$ is thus 2.1 at 1 µm which can be compared to the ratio obtained from the single event distribution measurements, which became 2.5. The difference in the ratio is about 20 per cent, which may reflect the experimental uncertainty.

EXPOSURE RATE DRIFT AND FLUCTUATIONS

The anode current and high voltage fluctuations given above show that the fluctuations of the exposure over a measurement time interval (~ 5 s) is expected to be less than 10^{-4} (σ_{rel}). Such fluctuations were kept at least a factor 5 below the actual measured relative standard deviations also at small object sizes with the use of gas multiplication. Thus monitoring was in this case not necessary for corrections of short term fluctuations. However, in order to detect and possibly correct for disturbances giving odd fluctuations or to correct for a linear exposure rate drift, a monitor chamber may by useful. Such a chamber is usually placed as close to the x-ray tube as possible, to get large chamber currents.

It follows from equation 1 and the results in Fig. 3 that

$$\sigma_{rel,x} \sim d^{-0.31} \, Q^{-0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

with previous notations. A k-fold increase in diameter of a spherical monitor chamber will thus give a reduction in $\sigma_{rel,x}$ for unchanged exposure rate according to $k^{-1.19}$. For instance doubling the diameter gives a reduction of about a factor 2 in $\sigma_{rel,x}$. This points to the use of a large transmission monitor ionization chamber.

Throughout our measurements monitoring was never deemed necessary and no exclusions of extreme values were made.

For a typical measurement of σ_{rel} with no apparent drift a least square linear fit to the data would yield a regression coefficient corresponding to a drift of 0.05 ± 0.06 per cent for 50 consecutive measurements of the current. This gives an upper limit of the drift of 0.1 per cent (95 per cent level of confidence) over one measurement sequence (about 300 s). If we corrected for such linear drift the estimated residual standard deviation was within 0.5 per cent of the original value.

DISCUSSION

Various contributions to σ_{rel}, other than those theoretically predicted as discussed by Kellerer (1968), has earlier been discussed in detail by Bengtsson et al. (1969) and Bengtsson, Lindborg (1974).

In the electrical *measuring system* the minimum σ_{rel} is determined mainly by the Poisson fluctuations of the electrons collected on the feedback capacitor at each integration and the input noise of the electrometer amplifier. With this equipment it was possible to get a relative standard deviation of 0.5×10^{-4} in repeated measurements of 100 pC. The expected Poisson fluctuation is 0.4×10^{-4}. The input noise to the amplifier is to a large extent proportional to stray capacitances and was made negligible by use of a very short cable (< 20 cm) between the chamber and electrometer.

The *anode current* variations were estimated to be less than 0.5×10^{-4} for currents between 0.15 and 13 mA. The *high voltage* fluctuation during short times (seconds) were less than 1×10^{-4}. With this radiation quality these voltage fluctuations will result in an exposure variation of less than 0.7×10^{-4}.

The *leakage current* of the whole measuring system was estimated to be in the range 1 to 15 fA for these measurements. A mean value for a large number of leakage current measurements was 5 fA. This will not cause any significant contribution to σ_{rel} at the ionization currents used.

One of the advantages with multi-event detection is that the *noise level* will be reduced compared with the signal level. For the proportional counter serie, which was performed at smaller absorbed doses and thus broader $f(z,D)$-distributions than in the ionization chamber serie, measurements were made with different gas gain at each object size. In Fig. 4 is illustrated how the signal to noise ratio is increased with an increase in gas gain. A limitating factor at very small object sizes should be the extended Townsend avalanche which will increase the relative variance. However, at the smallest object size (0.08 µm) σ_{rel} was neither decreased nor increased for gas gains between 500 and 800 which should indicate that the noise level is negligible at these gas gains and that the extended avalanche did not seriously disturb the experiments. This finding was further confirmed from an estimation of the avalanche properties according to Glass, Gross (1972, Fig. 2). If a counter with a helix had been used it should have been possible to reduce the avalanche extension. Also the use of propane gas instead of methane gas should have been favourable (Srdoc, 1970). With such modifications in the conditions a further reduction of the object sizes could have been possible.

For the object size at 0.04 µm it was not possible to get a sufficiently high gas multiplication before electrical breakdown did occur. For the ionization chamber measurements it was not possible to get reliable results below 0.7 µm. One possible reason for this could be an excessive leakage of air into the Al-shielding tube.

The results obtained here from variance measurements both with ionization chamber and proportional counter are in agreement with our own pulse height measurements and those reported by Braby and Ellett (1971). If an extrapolation of their results is made down to 0.08 µm a difference of about 30 per cent is obtained in comparison with our variance measurements, which is in agreement with the estimated uncertainty given above.

Booz (1976) tried to correlate $\bar{y}_D$ with $\bar{y}_F$ through a relation $\bar{y} = \bar{y} \cdot d^a$ where a = 0.25 for walled chambers. This relation may be used for deriving $\bar{y}_F$ from $\bar{y}_D$ in Fig. 4. This relation gave $\bar{y}_F$-values in reasonable agreement with those reported by Booz (1976).

Finally a possible radiobiological application will be mentioned. It has been proposed by Kellerer-Rossi (1971) that the yield of primary lesions is

$$\varepsilon(D) = k(\zeta D + D^2)$$

Thus at absorbed doses small compared to ζ the linear term will dominate and RBE-values obtained in this dose-interval for ^{60}Co gamma and conventional x-rays will be constant and proportional to the ratio of ζ of the different radiations. This ratio obtained from the variance measurements seem to be constant for the two radiations investigated. One conclusion should thus be that it is unlikely to derive any site diameter from RBE-measurements with these radiation qualities in that dose interval.

CONCLUSION

The reported results from variance measurements in a highly stabilized x-ray beam have given results in agreement with those reported by others in the range of object sizes where a comparison has been possible. It has thus been shown that the technique can be applied to radiation beams other than those from radioactive nuclides under certain conditions and that information about dose mean lineal energy can be obtained for smaller object sizes than with the traditional microdosimetry technique.

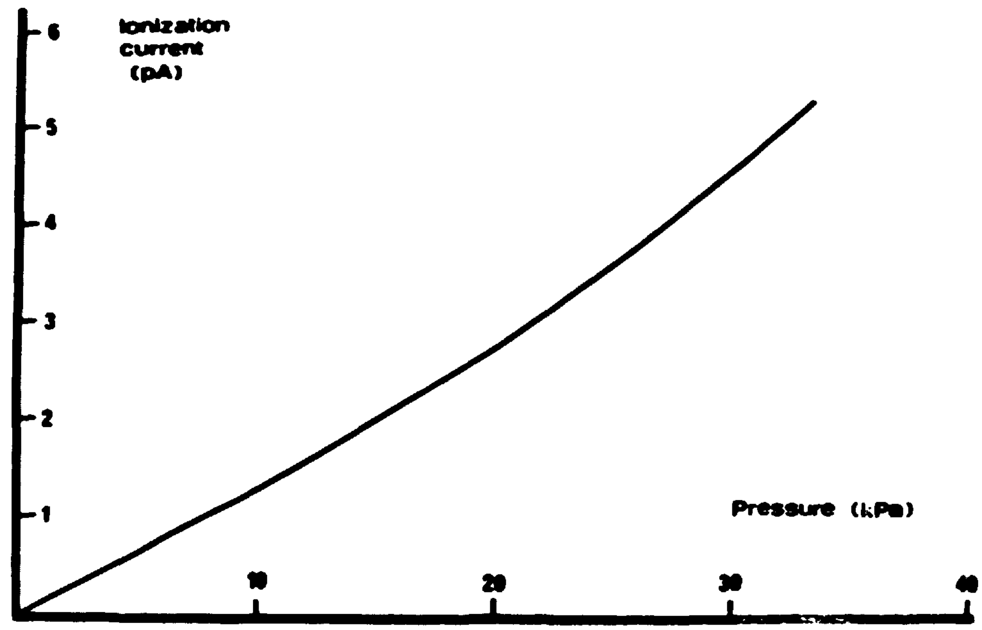

Fig. 1 Ionization current for different pressures in the proportional counter at unity gas gain ($\bar{G}$ = 1).

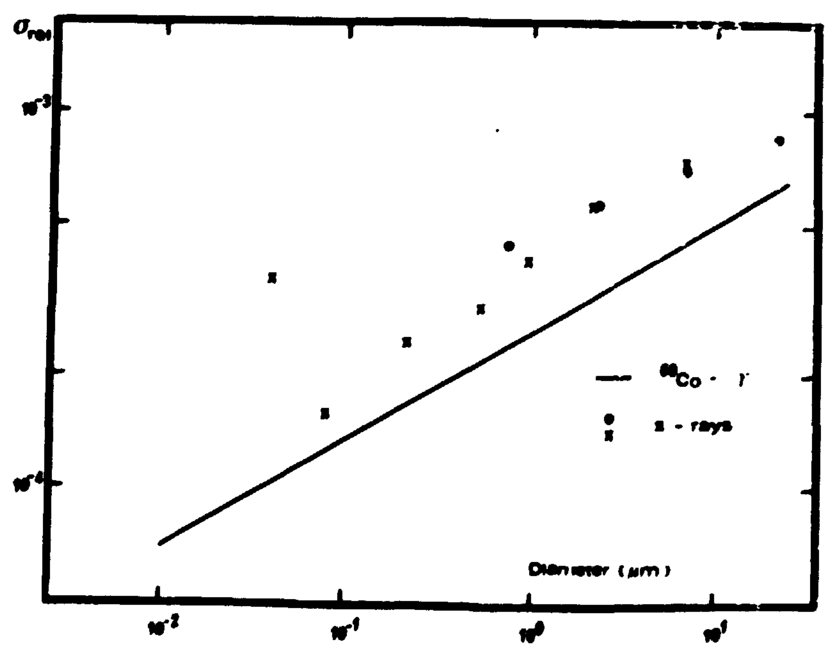

Fig. 2 Result of variance measurements given as one relative standard deviation for different object sizes.

— ^{60}Co-γ Bengtsson, Lindborg (1974)

o x-rays ionization chamber serie

x x-rays proportional counter serie

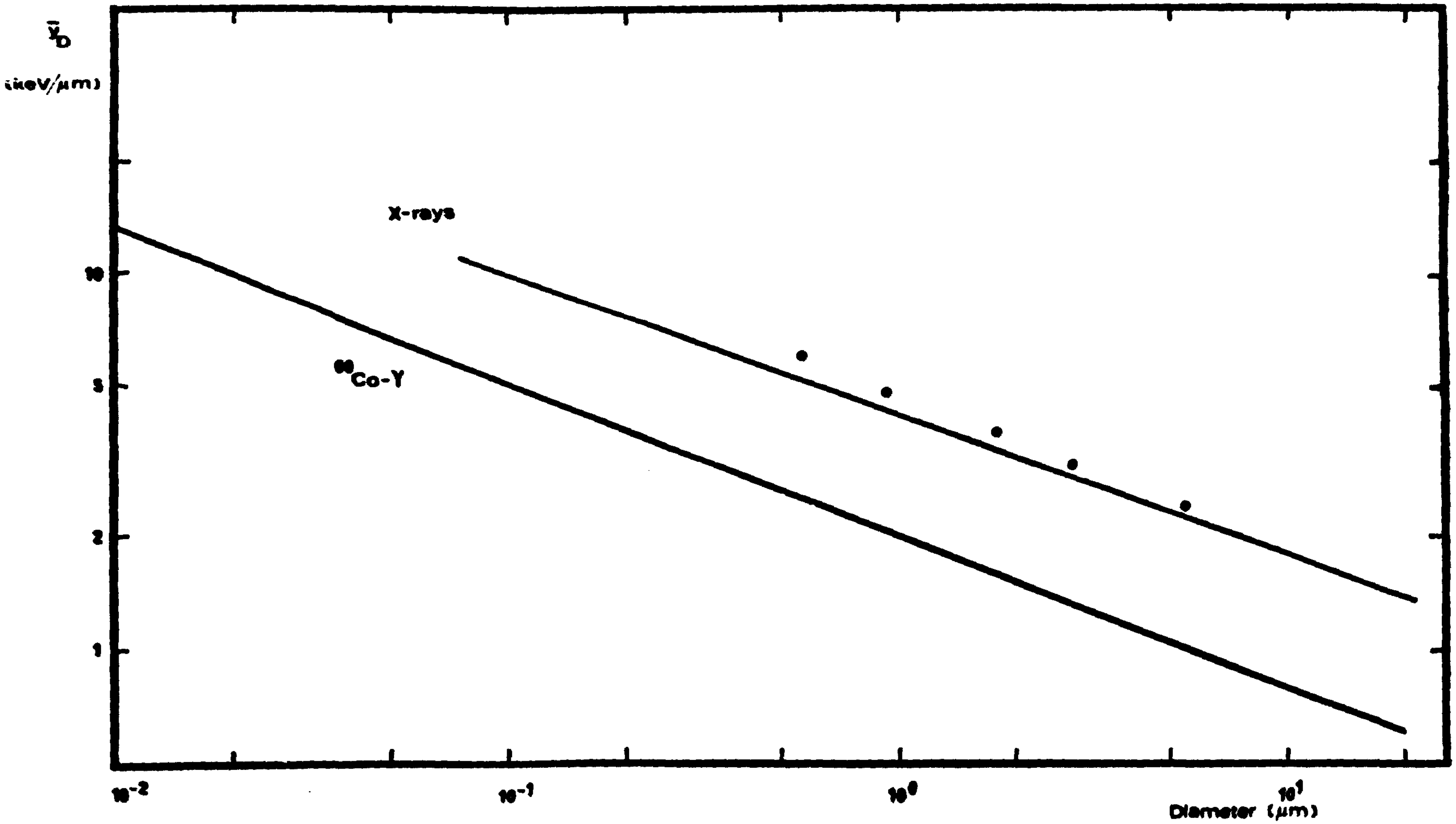

Fig. 3 Dose mean lineal energy for different object sizes

—— ^{60}Co variance measurements Bengtsson, Lindborg (1974)

— x-rays - " - this report

••• Pulse height measurements Braby-Ellett (1971)

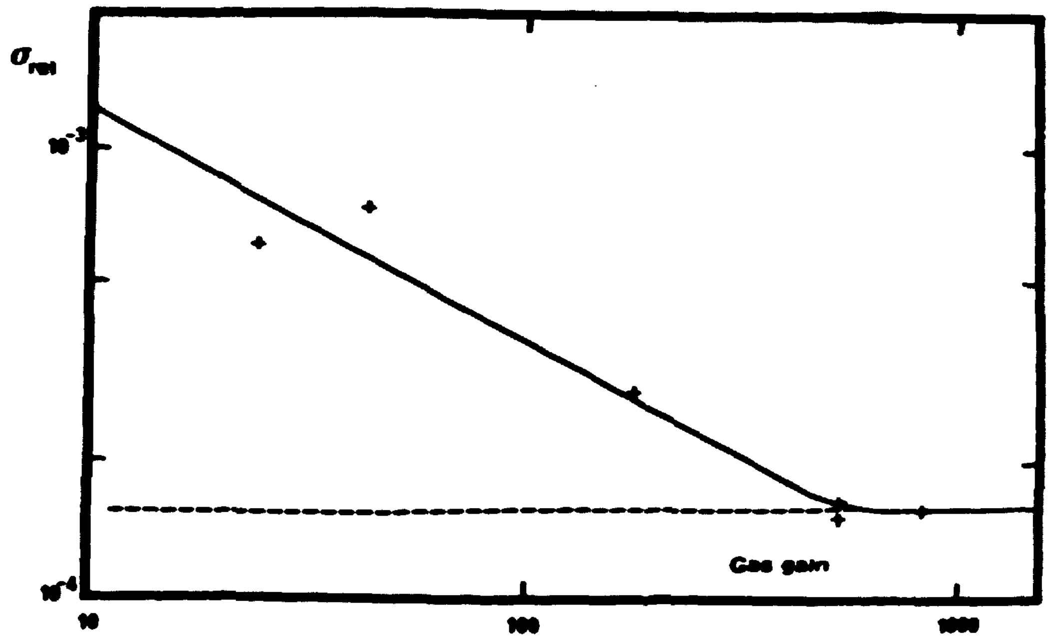

Fig. 4 σ_{rel} for different gas gain at an object size of 0.08 µm.
The dotted line should approximate the expected fluctuations.

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