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Radiation Induced Chromosome Aberrations and the Poisson Distribution

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Summary. Data on the distribution of dicentrics and acentrics observed when human lymphocytes are cultured for 48 h after irradiation by X-rays, γ-rays, and neutrons are presented.

Analysis shows that for dicentrics, the observed distribution for X-rays, γ-rays, and fission neutrons may be described by Poisson statistics but for higher energy neutrons overdispersion is observed. The phenomenon of overdispersion is also observed for acentrics irrespective of the radiation used.

The possibility that overdispersion results from the variations of dose in sensitive sites leads to the conclusion that for dicentrics the site size is considerably larger than the 1–2 μm diameter derived by applying the dual action theory to the dose effect relationships. This larger site may well be the cell nucleus.

Introduction

Lloyd et al. (1975, 1976) have published experimental data for the yield of chromosome aberrations in cultured human lymphocytes as a function of absorbed dose for various neutron, X-ray, and γ-ray spectra. No data, however, were published on the distribution of the aberrations amongst the cells. This information is presented here together with the results of tests to determine how well Poisson statistics describe the observed frequency distributions.

Lloyd et al. displayed their data in three aberrration groups. These were dicentrics (tri- and tetracentrics being scored as two and three dicentrics respectively), acentrics which are really excess acentrics after allowing one for each dicentric and centric ring, and total aberrations which is the sum of dicentrics, excess acentrics and centric rings. Thus total aberrations are identical to the total number of acentrics. The observed distributions of dicentrics and acentrics among the cells for each type of radiation and each dose are given in Tables 1–4.

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Table 1. The distributions of dicentrics among the cells at different doses for various low LET radiations

Radiation	Dose rads	Cells scored	Dicentrics	Distribution							
				0	1	2	3	4	5	6	7
250 kVp X-rays	5	3325	9	3316	9						
100 rad/min	10	4693	28	4665	28						
	25	3547	49	3498	49						
	50	2652	111	2547	99	6					
	100	1869	200	1683	172	14					
	200	266	99	189	57	18	2				
	250	183	100	109	53	17	3	1			
	300	293	219	130	120	33	7	3			
	400	247	323	75	75	61	23	10	1	2	
	600	100	224	9	22	29	21	16	2	0	1
	800	30	117	1	1	5	6	4	7	5	1
^{60}Co γ-rays	25	6883	48	6835	48						
50 rad/min	50	4917	119	4801	113	3					
	100	2366	142	2228	134	4					
	200	462	105	369	81	12					
	300	494	242	311	135	38	9	1			
	500	173	234	48	62	34	15	11	3		
	800	89	301	1	6	22	13	30	11	5	1
^{60}Co γ-rays	25	6746	47	6699	47						
18 rad/h	50	4429	55	4374	55						
	100	1914	107	1815	91	8					
	200	946	166	787	152	7					
	400	408	267	211	140	45	11	1			
	800	97	152	23	25	31	8	9	1		

The Method of Analysis

The object of the statistical analysis is to describe how well Poisson statistics represent the distributions of aberrations among the cells. The test used is that adapted by Papworth and described by Savage (1970) in which the variance and the mean of the observed distributions are compared in order to judge whether they are significantly different.

From each distribution of aberrations among the cells given in Tables 1–4, the total number of cells N, the mean number of aberrations per cell Y, and an estimate σ^2 of the population variance may be derived. A coefficient of dispersion d is defined by Eq. (1).

$$d = \frac{(N-1)\sigma^2}{Y}. \tag{1}$$

By considering the probability of occurrence of all possible distributions of aberrations subject to constant values of N and Y Radharkrishna Rao and Chakravarti

Table 2. The distributions of excess acentrics among the cells at different doses for various low LET radiations

Radiation	Dose rads	Cells scored	Acentrics	Distribution								
				0	1	2	3	4	5	6	7	8
250 kVp X-rays	5	3325	45	3282	41	2						
100 rad/min	10	4693	63	4632	59	2						
	25	3547	63	3487	57	3						
	50	2652	70	2588	58	6						
	100	1869	129	1756	98	14	1					
	200	266	48	222	40	4						
	250	183	89	117	49	13	2	2				
	300	293	153	193	64	27	5	3	0	0	0	1
	400	247	174	134	76	22	9	3	3			
	600	100	112	42	21	25	8	3	1			
	800	30	93	3	5	6	3	4	4	4	1	
^{60}Co γ-rays	25	6883	62	6829	46	8						
50 rad/min	50	4917	144	4779	132	6						
	100	2366	137	2246	107	12	0	0	0	1		
	200	462	83	391	59	12						
	300	494	224	343	98	37	12	4				
	500	173	208	63	52	33	15	5	5			
	800	89	227	11	22	12	18	12	7	6	0	1
^{60}Co γ-rays	25	6746	74	6677	64	5						
18 rad/h	50	4429	67	4362	67							
	100	1914	91	1830	77	7						
	200	946	123	837	95	14						
	400	408	148	288	96	20	4					
	800	97	89	44	26	20	5	2				

(1956) have shown that if the underlying process is Poissonian, the mean value of $d = N - 1$, and the variance of d, var $d = 2(N - 1)(1 - 1/NY)$. Thus the quantity u defined by Eq. (2) approximates to a unit normal deviate.

$$u = \frac{d - (N - 1)}{\sqrt{\text{var } d}} . \tag{2}$$

A positive value of u indicates over-dispersion while a negative value indicates under-dispersion. If the magnitude of u is greater than 1.96 then the under or over-dispersion is significant because there is only a 5% chance that the magnitude of u will exceed 1.96 when the underlying distribution is Poissonian.

Results

Tables 5 and 6 give the value of u and σ^2/Y at all doses for each combination of radiation and aberration type. Referring to Table 5, the values of u for dicentrics in

Table 3. The distributions of dicentrics among the cells at different doses of neutron radiations

Radiation	Dose rads	Cells scored	Dicentrics	Distribution							
				0	1	2	3	4	5	6	7
14.7 MeV *D–T*	5	2000	34	1968	30	2					
neutrons	10	763	25	740	21	2					
	25	723	50	678	41	3	1				
	50	568	65	509	54	4	1				
	101	472	202	317	118	28	8	1			
	152	303	202	178	67	41	15	2			
	202	243	206	108	79	43	11	2			
	303	67	100	15	27	14	5	2	3	0	1
MRC cyclotron	27	894	108	797	89	5	3				
16 MeV	54	342	96	263	67	8	3	1			
deuterons	108	143	100	74	44	19	6				
on thick	162	103	101	40	37	16	8	2			
Be target	216	74	105	17	27	16	11	2	1		
	270	60	99	14	16	16	9	2	2	1	
	324	49	104	5	11	14	12	6	1		
BEPO fission	50	269	109	176	79	12	2				
neutrons	75	78	47	44	25	5	4				
	100	115	94	52	40	17	5	0	1		
	150	90	114	25	31	24	6	3	1		
	200	84	138	17	24	21	17	4	1		
	250	59	125	6	13	20	14	3	1	1	1
	300	37	97	1	10	7	7	9	2	1	

cells irradiated by ^{60}Co γ-rays and X-rays lie between -2.69 and 2.93, 13 of the values are negative, 11 positive, and only four have a magnitude which exceeds 1.96. There is, therefore, no reason to reject the postulate that the dicentrics follow the Poisson distribution. For acentrics, however, two values of u are negative and 22 positive, 17 of which are greater than 1.96, presenting clear evidence of overdispersed distributions. The values of the relative variance σ^2/Y in Table 5 show no marked systematic variation with dose. The observed distributions of total aberrations were analysed in the same way and showed overdispersion. The values of σ^2/Y on average lay between those for dicentrics and acentrics but closer to the acentric value.

For neutron radiations (Table 6) acentrics are over-dispersed while for dicentrics the evidence is conflicting. For 14.7 MeV neutrons there is clear evidence for overdispersion. For the cyclotron generated neutrons the evidence, while less convincing, favours over-dispersion, but for the BEPO fission spectrum, the distribution is Poissonian. The analysis of total aberrations yielded a mean value of σ^2/Y close to that for acentrics.

In scoring aberrations there is the possibility that scorer error could bias the observed distributions. Since there is more uncertainty in identifying acentrics than dicentrics, this bias is more likely in the distribution of acentrics and total aberra-

Table 4. The distributions of excess acentrics among the cells for different doses of neutron radiations

Radiation	Dose rads	Cells scored	Acentrics	Distribution										
				0	1	2	3	4	5	6	7	8	9	10
14.7 MeV	5	2000	32	1972	24	4								
D–T neutrons	10	763	11	752	11									
	25	723	38	689	30	4								
	50	568	66	512	47	8	1							
	101	472	166	356	77	31	5	3						
	152	303	144	201	71	22	7	2						
	202	243	166	127	73	37	5	1						
	303	67	67	31	16	12	6	1	1					
MRC cyclotron	27	894	74	827	61	5	1							
16 MeV	54	342	96	267	60	10	4	1						
deuterons	108	143	63	94	37	10	2							
on thick	162	103	73	57	27	13	5	0	1					
Be target	216	74	76	33	22	12	5	0	1	0	0	0	0	1
	270	60	76	26	12	11	6	4	0	0	0	1		
	324	49	69	16	15	8	7	1	1	0	0	1		
BEPO fission	50	269	101	194	54	17	3	1						
neutrons	75	78	49	49	16	8	3	2						
	100	115	87	64	30	13	4	1	3					
	150	90	117	32	27	17	8	2	3	0	0	0	1	
	200	84	156	19	18	23	14	6	1	1	1	1		
	250	59	138	15	11	14	5	1	5	5	1	1	0	1
	300	37	107	5	7	3	10	4	3	3	1	1		

tions among the cells. The most likely source of error would be to overlook an acentric in cells which have only one acentric, on the grounds that if an aberration is seen in a cell, that cell is likely to be scrutinized more closely. The magnitude of the bias this could introduce was estimated by transferring about 10% of the number of cells in column 0 to column 1 in Table 2 and recalculating σ^2/Y. All values of σ^2/Y were lower than the corresponding values in Table 5 but the reduction was so small that still only two of the 24 values were less than 1. We are convinced that 10% is an upper limit for the loss of information due to this effect and thus conclude that such a bias does not alter our conclusion that acentrics are over-dispersed.

Discussion

A few other authors have published distributions of aberrations for human lymphocytes. Brenot et al. (1974) conclude that for dicentrics produced by cobalt-60 γ-rays, and by a neutron beam from the reactor Harmonie, Poisson statistics adequately describe the observed distributions. From their data obtained from the neutron beam however, there is evidence that the relative variance is greater than 1 at doses less

Table 5. Values of u and σ^2/Y for different doses of low LET radiations

Radiation	Dose rads	u		$\sigma^2/Y \pm$ SE	
		Dicentrics	Acentrics	Dicentrics	Acentrics
^{60}Co	25	−0.40	7.27	0.99 ± 0.02	1.12 ± 0.02
18 rads/h	50	−0.58	−0.71	0.99 ± 0.02	0.985 ± 0.02
	100	2.93	3.32	1.09 ± 0.03	1.11 ± 0.03
	200	−1.97	2.16	0.91 ± 0.05	1.10 ± 0.05
	400	−0.33	1.04	0.98 ± 0.07	1.07 ± 0.07
	800	0.06	1.05	1.01 ± 0.14	1.15 ± 0.14
^{60}Co	25	−0.40	14.7	0.99 ± 0.02	1.25 ± 0.02
50 rads/min	50	1.32	2.70	1.03 ± 0.02	1.05 ± 0.02
	100	−0.11	11.6	1.00 ± 0.03	1.34 ± 0.03
	200	0.05	1.71	1.00 ± 0.07	1.11 ± 0.07
	300	1.56	6.54	1.10 ± 0.06	1.42 ± 0.06
	500	1.39	3.02	1.15 ± 0.11	1.32 ± 0.11
	800	−2.69	2.24	0.59 ± 0.15	1.34 ± 0.15
250 kVp X-rays	5	−0.10	3.12	1.00 ± 0.02	1.08 ± 0.02
100 rads/min	10	−0.28	2.46	0.99 ± 0.02	1.05 ± 0.02
	25	−0.58	3.30	0.99 ± 0.02	1.08 ± 0.02
	50	2.44	5.33	1.07 ± 0.03	1.15 ± 0.03
	100	1.03	5.99	1.03 ± 0.03	1.20 ± 0.03
	200	1.35	−0.12	1.12 ± 0.09	0.99 ± 0.09
	250	0.95	2.08	1.10 ± 0.10	1.22 ± 0.10
	300	−1.05	7.68	0.91 ± 0.08	1.63 ± 0.08
	400	1.34	4.63	1.12 ± 0.09	1.42 ± 0.09
	600	−1.32	1.89	0.81 ± 0.14	1.27 ± 0.14
	800	−0.89	1.48	0.77 ± 0.26	1.39 ± 0.26

than 100 rads but less than 1 at about 200 rads. Bauchinger and Schmid (1973) and Bauchinger et al. (1974) observed a Poisson distribution of dicentrics produced by 220 kV X-rays and 3 MeV electrons while for 15 MeV neutrons Schmid and Bauchinger (1975) obtained relative variances between 1.12 and 1.22 for doses in the range 125–500 rads in good agreement with our results. Holmberg (1978) observed relative variances for dicentrics in the range 1.13–1.23 for mono-energetic neutrons of energy 0.8–2.35 MeV at dose levels of 20–35 rads. Virsik et al. (1977) claim that dicentrics induced by 150 kV and 30 kV X-rays conform to the Poisson distribution. Bearing in mind the errors involved in estimating relative variance, see Tables 5 and 6, none of the above results differ significantly from our own. Bauchinger et al. in some of their papers distinguish between acentrics which are formed with and without dicentrics or centric rings but there is insufficient information to make a comparison of acentric distributions. Some further results by Haag et al. (1977) for dicentrics in pig lymphocytes support our observations of increasing relative variance with increasing neutron energy.

Our results pose some rather interesting questions. Why should the dicentrics conform to a Poisson distribution for electromagnetic radiations but be probably

Table 6. Values of u and σ^2/Y for different doses of neutron radiations

Radiation	Dose rads	u		$\sigma^2/Y \pm$ SE	
		Dicentrics	Acentrics	Dicentrics	Acentrics
14.7 MeV neutrons	5	3.25	7.54	1.10 ± 0.03	1.23 ± 0.03
	10	2.56	−0.27	1.13 ± 0.05	0.99 ± 0.05
	25	3.31	3.07	1.17 ± 0.05	1.16 ± 0.05
	50	1.75	3.72	1.10 ± 0.06	1.22 ± 0.06
	101	2.29	6.50	1.15 ± 0.06	1.42 ± 0.06
	152	3.79	3.61	1.31 ± 0.08	1.29 ± 0.08
	202	0.12	0.22	1.01 ± 0.09	1.02 ± 0.09
	303	2.12	2.28	1.37 ± 0.17	1.39 ± 0.17
MRC cyclotron neutrons	27	2.97	2.87	1.14 ± 0.05	1.13 ± 0.05
	54	2.65	4.02	1.20 ± 0.08	1.31 ± 0.08
	108	0.41	0.64	1.05 ± 0.12	1.07 ± 0.12
	162	0.43	2.48	1.06 ± 0.14	1.35 ± 0.14
	216	−0.33	7.06	0.95 ± 0.16	2.16 ± 0.16
	270	1.03	4.90	1.19 ± 0.18	1.90 ± 0.18
	324	−1.29	3.67	0.74 ± 0.20	1.74 ± 0.20
BEPO fission	50	−0.83	3.06	0.93 ± 0.09	1.26 ± 0.09
	75	0.85	3.61	1.14 ± 0.16	1.58 ± 0.16
	100	0.65	5.01	1.09 ± 0.13	1.66 ± 0.13
	150	−0.19	5.05	0.97 ± 0.15	1.75 ± 0.15
	200	−0.62	2.61	0.90 ± 0.15	1.40 ± 0.15
	250	−0.47	7.47	0.91 ± 0.18	2.38 ± 0.18
	300	−0.80	2.27	0.81 ± 0.23	1.53 ± 0.23

over-dispersed for neutrons? Why should acentrics be over-dispersed for all radiations? In the following it is proposed to discuss possible answers to these questions.

In the past, the tendency has been to explain deviations from the Poisson distribution of aberrations among cells in terms of the characteristics of the biological system. Savage (1970) has successfully explained under-dispersion in terms of the distortion hypothesis in which the total number of possible aberrations is restricted by the small number of chromosomes in each nucleus. It is not expected that dicentrics would be under-dispersed in human lymphocytes, which contain 46 chromosomes, except at high doses where the effects of saturation reduce the aberrations seen in a cell. Explanation of over-dispersion relied upon the postulate that the cell population is not homogeneous. On the other hand, Kellerer (1973) has considered the possibility that statistical variations of energy deposition lead to over-dispersion of aberrations and it is intended to concentrate on this proposal to investigate how well our observed relative variances may be explained.

In the theory of dual radiation action, Rossi and Kellerer (1974) assume that the biological effect is related statistically to the specific energy z in a critical volume which may be the whole cell, the cell nucleus of some region within the nucleus. The specific energy is composed of single increments of specific energy of which the size

distribution is denoted by $f_1(z)$, ICRU (1971). Thus the specific energy z is a statistical variable the mean of which is the absorbed dose D. Rossi and Kellerer (1974) show that proportionality to z^2 of the expected number of aberrations in a site where the specific energy is z, leads to a dose effect relationship that is described by Eq. (3) where k is a constant and ζ is defined by Eq. (4)

$$Y = k(\zeta D + D^2)\,, \tag{3}$$

$$\zeta = \frac{\int_0^\infty z^2 f_1(z)dz}{\int_0^\infty z f_1(z)dz}\,. \tag{4}$$

Kellerer (1973) assumes that for a given z the aberrations are distributed as the Poisson distribution and shows that because the value of z varies from site to site, the distribution of aberrations amongst the sites is over-dispersed compared to Poisson with relative variance σ^2/Y given by Eq. (5), where ζ_2 and ζ_3 are ratios of the third and fourth moments to the first moment of the distribution $f_1(z)$ respectively. Kellerer further shows that Eq. (6) is a good approximation to Eq. (5) although always under-estimating the value of σ^2/Y.

$$\frac{\sigma^2}{Y} = \frac{1 + k(\zeta_3 + 4\,\zeta_2 D + 4\,\zeta D^2)}{\zeta + D}\,, \tag{5}$$

$$\frac{\sigma^2}{Y} = 1 + 4\,k\zeta D\,. \tag{6}$$

Lloyd et al. analyse their yield data using the equation $Y = \alpha D + \beta D^2$ so that using Eq. (3), k and ζ may be estimated. A site size can then be deduced from ζ using measured or calculated $f_1(z)$ spectra for the radiations.

The values of site size given in Table 7 were deduced from Booz (1975) for X-rays and γ-rays and from the computer programme described by Edwards (1974) and Edwards and Dennis (1975) for the neutron spectra. The product $k\,\zeta$ may also be used to predict values of σ^2/Y from Eq. (6).

Values for $k\zeta$, site diameter with and without the saturation correction of Rossi and Kellerer (1974), and σ^2/Y predicted from Eq. (6) are shown in Table 7 for all the radiations considered. Comparisons with Tables 5 and 6 show that for all radiations the predicted values exceed the measured values particularly at high doses. Furthermore, the strong predicted dependence of σ^2/Y on dose is not evident in the measurements. If the theory of Kellerer (1973) is to explain numerically the distribution of dicentrics among the cells, then the values of $k\zeta$ must be much smaller than that given by the initial slope of the yield curves. If the site size over which ζ was determined were larger ζ would be smaller. Table 8 shows predicted values of relative variance for all radiations assuming for the same value of k, a site diameter of 7 μm which is about the size of the cell nucleus. These predictions agree more closely although not perfectly with the observations, the main discrepancy occurring because the predicted increase of relative variance with dose is not observed which implies that the basic assumption that the yield is proportional to z^2 is no longer true

Table 7. Predicted values of site diameter and relative variance from the fitted coefficients α and β for dicentric yield using the dual action theory of Rossi and Kellerer (1974)

Radiation	$\alpha = k\,\zeta$	$\beta = k$	ζ	Site diameter (μm)	Site diameter with saturation correction (μm)	Predicted values of σ^2/Y		
						30 rads	100 rads	300 rads
^{60}Co γ-rays	1.6×10^{-4}	5×10^{-6}	31	1.1	1.1	1.02	1.06	1.19
250 kVp X-rays	4.8×10^{-4}	6.2×10^{-6}	77	1.1	1.1	1.06	1.19	1.58
14.7 MeV neutrons	2.6×10^{-3}	8.8×10^{-6}	300	2.4	1.3	1.31	2.0	4.1
Cyclotron generated neutrons	4.8×10^{-3}	6.4×10^{-6}	750	1.4	0.85	1.58	2.9	6.8
BEPO fission neutrons	8.3×10^{-3}	—	—	—	—	2.0	4.3	11

Table 8. Predicted values of σ^2/Y for each radiation assuming $Y = kz^2$, site size 7 μm and a value of k given by the coefficient β. The value of k taken for BEPO fission neutrons is 6×10^{-6}

Radiation	ζ for a site diameter of 7 μm	$k\zeta$	Predicted values of σ^2/Y at		
			30 rads	100 rads	300 rads
^{60}Co γ-rays	0.4	2×10^{-6}	1.00	1.00	1.00
250 kVp X-rays	0.8	5×10^{-6}	1.00	1.00	1.00
14.7 MeV neutrons	26	230×10^{-6}	1.03	1.09	1.28
Cyclotron generated neutrons	17	110×10^{-6}	1.01	1.04	1.13
BEPO fission neutrons	20	120×10^{-6}	1.01	1.04	1.14

Table 9. Predicted values of σ^2/Y assuming $Y = cz$ and site diameters of 1 and 7 μm

Radiation	$\alpha = c$	ζ at site diameter		Predicted values of σ^2/Y at	
		1 μm	7 μm	1 μm	7 μm
^{60}Co	1.6×10^{-4}	35	0.3	1.01	1.00
X-ray	4.8×10^{-4}	80	0.6	1.04	1.00
14 MeV neutrons	2.6×10^{-3}	1900	26	5.0	1.07
Cyclotron generated neutrons	4.8×10^{-3}	1400	18	7.7	1.09
BEPO fission neutrons	8.3×10^{-3}	1400	20	12.6	1.17

when applied to the larger site sizes. If the mean yield were assumed proportional to z, Kellerer (1973) shows that Eqs. (7) and (8) replace Eqs. (3) and (6) respectively.

$$Y = cD\,, \tag{7}$$

$$\frac{\sigma^2}{Y} = 1 + c\zeta\,. \tag{8}$$

Table 9 shows predicted values of σ^2/Y for each radiation using Eqs. (7) and (8) at site diametres of 1 and 7 μm. It is clear once again that the better agreement with observation is obtained by assuming a site diameter nearer 7 μm rather than 1 μm. Numerically the predicted values of σ^2/Y at 7 μm are fairly close to the observations but the prediction for the fission spectrum is somewhat higher than the observation.

A similar analysis for acentrics is more complex because they may be formed as the result of a one break or a two break process. Eq. 9 is an approximation to a model which takes into account both mechanisms. However there are three parameters (c, k, and ζ)

$$Y = cz + kz^2 = (c + k\zeta)D + kD^2 \tag{9}$$

to adjust for only two fitted coefficients (α and β) so that the ratio σ^2/Y cannot be calculated without more information. If it were valid to ascribe the overdispersion observed for X-rays and γ-rays to variations of dose in sensitive sites then a somewhat crude estimate of site diameter in the region of 0.5 μm may be obtained by using approximate Eqs. (7) and (8). Alternatively if one ascribes the excess dispersion due to neutrons to the theory, then a site size in the region of 7 μm is obtained consistent with the one previously derived for the dicentric distributions.

The analysis presented here permits some conclusions to be drawn and highlights some outstanding problems. The dual action theory requires two site sizes to explain the production of aberrations in cells. The site size required to predict the mean yield is commonly interpreted as an interaction distance between lesions within a cell nucleus, whereas the site size which determines the distribution of aberrations per cell is a larger sensitive region which may well be the total nucleus of the cell. For these larger site volumes the mean yield of aberrations is not a function of z alone; there is much convincing evidence that the distribution of energy within a cell nucleus is important. This invalidates the assumption that for a given value of z the distribution of aberrations is Poissonian and indicates a short-coming of the theory presented by Kellerer (1973). A valid theoretical derivation of aberration distributions between cells should take into account the distribution of energy within the cell as well as the total energy. A complete treatment of the problem must involve in addition other factors, for example distortion. However the fact that at least for dicentric production, X-rays, and γ-rays give a closely Poissonian distribution and that a simple model involving the distribution of dose amongst cells leads for neutron radiation to estimates of σ^2/Y in reasonable agreement with the observations indicates that these other factors are negligible.

Conclusions

An attempt has been made to quantitatively relate the distribution of chromosome aberrations among cells irradiated by radiations of different quality to the distribution of energy in sensitive sites. It is shown that such a model predicts distributions which are overdispersed compared to Poisson and that generally radiations of higher LET produce distributions of greater dispersion. Data are presented which show that both acentrics and dicentrics in human lymphocytes have a greater dispersion when the blood is irradiated with neutrons than with γ-rays. Comparing the observations and predictions it is shown that a sensitive volume of about 7 μm in diameter, that is of dimensions close to the cell nucleus, is required. This contrasts with the site size or interaction distance of about 1 μm required to predict RBE effects using the dual radiation action theory.

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