EFFECTS FROM IRRADIATION OF RICE SEED WITH GAMMA RAYS AND NEUTRONS ON SEVERAL CHARACTERISTICS OF THE R_1 GENERATION[1]

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During the past 15–20 years there has been intensive research devoted to the relationship of atomic energy to various fields of biology. One of the phases receiving serious attention is the induction of mutations in economic plants which might prove beneficial to man. Most of the research of this type has involved exposure of dormant seeds to various types of ionizing radiation. Although favorable results have been reported in several experiments, an evaluation of the potential role of induced mutations and development of the most appropriate procedures for utilizing these mutations in plant breeding programs will require additional research.

In addition to gene mutations, both detrimental and beneficial, ionizing radiations cause damage to the living organism of two general types, one being an effect on the cytoplasm, which may cause immediate or ultimate death of the cell, and the other being damage to the chromosomes. Before the most efficient use can be made of atomic energy for the induction of beneficial genetic changes, it is necessary to have basic information concerning the damage caused by various forms and dosages of radiation. Furthermore, it is probable that all species of economic plants are not affected to the same degree by radiation, making it necessary to conduct research with each species, individually.

The experiments reported in this paper involved irradiation of dormant seed of a variety of cultivated rice, Nato, with two types of ionizing radiation, gamma rays from Co^{60} and neutrons, and a study of the detrimental effects on several characteristics of the R_1 generation.

Review of Literature

The literature dealing with effects of ionizing radiation on living organisms

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has become far too voluminous to permit a complete review here. Consequently, only a limited number of publications that appear to be especially pertinent to the research being reported here will be reviewed.

Muller in 1927 first presented evidence that ionizing radiation can cause structural changes in chromosomes. This discovery was soon extended to other species of plants by several investigators.

Researches with pollen grains of *Tradescantia* have contributed greatly to the knowledge concerning relation of chromosome aberration frequency to dose of radiation. Sax (1938, 1940) irradiated pollen grains of *T. reflexa* with dosages of X-rays ranging from 100 γ to 1,200 γ at a constant intensity of 25 γ per minute and found that the frequency of simple deletions, caused by single chromosome breaks, had a linear relationship to total dosage. However, the frequency of two-break aberrations, such as interchanges, increased geometrically in relation to dosage. It was suggested from these results that the two-break aberrations are caused by two independent hits. Giles (1943, 1954) found from irradiation of *Tradescantia* pollen grains with varying dosages of fast neutrons that the frequencies of all types of aberrations, whether one- or two-break increased linearly with dosage. He concluded that unlike X-rays, all aberrations produced by fast neutrons are the result of single hits.

From a study of mitosis in root tips of seedlings irradiated with varying dosages of fast neutrons, Marshak (1939) reported widely different effects from a given dosage on chromosome changes in the three species *Vicia faba, Pisum sativum* and *Solanum lycopersicon.* More than 10 times as much radiation was required to cause 50% of abnormal anaphase figures in *S. lycopersicon* as in *V. faba.*

Genter and Brown (1941) were among the first to study the effect of increasing dosage of ironizing radiation applied to dormant seed on plant survival. From X-ray dosages ranging from 2,160 γ to 26,000 γ with the garden bean, they found that emergence of seedlings and plant survival decreased with increasing dosage but not at a constant rate.

Gustafson (1944) tested the response of dormant seeds of several agricultural species to varying dosages of X-rays, using survival to maturity and seed production as criteria of tolerance. The maximum dose that a species could withstand and survive, called critical dose, varied widely for different species, ranging from only 5,000 γ for sunflower to 92,000 γ for white mustard. Species of the grass family were intermediate in tolerance.

McKey (1951) reported results from an intensive series of experiments involving irradiation of barley seed with varying dosages of X-rays and neutrons. Plant survival was reduced greatly by the maximum X-ray dose of 25,000 γ and by the higher neutron doses. For both types of radiation, decreasing percentages of survival occurred from increasing dosages, with approximately equal effects of comparable doses of the two forms of radiation. However, the results were somewhat different in effect on plant fertility. Following X-ray treatments, the reduction in fertility tended to level off before the maximum dosage was reached, with a minimum seed set of 60–70 per cent. On the other hand, the higher neutron doses reduced seed set to about 20 per cent. The frequency of cells with chromosome fragments in the first cycle of mitosis during germination of the seed showed a linear relationship to dosage for both types of radiation although the slope of the curve tended to level off at high dosages due to a "saturation effect". It was suggested that the pronounced saturation effect on plant survival and the tendency to show such an effect on chromosome aberration arose because the primordium in the dormant barley seed is multicellular and high X-ray dosages cause death of severely affected cells but other cells of the same primordium which are not so severely affected develop into a seedling.

Ehrenberg *et al.* (1953) also reported results with barley which indicated that cells of the spike primordium receiving a strong dosage of X-rays are eliminated, leading to the development of the seedling from other cells that were not so severely exposed. He referred to this condition as "intrasomatic selection". The effect was noted also in percentage of cells with chromosome aberrations during mitosis in root tips. The frequency of aberrations increased with dosage up to 15,000 r but levelled off at that dosage.

Caldecott and associates (Caldecott, 1955; Caldecott and Smith, 1952; Caldecott *et al.*, 1952, 1954) have also studied the effects of X-ray and neutron radiation of dormant barley seeds on several characteristics of the first generation. X-ray dosages ranged from 250 r to 32,000 r. The frequencies of chromosome bridges during mitosis in root tips and of interchanges during meiosis in spikes were essentially the same for each X-ray dose. It was concluded that almost all aberrations induced in dormant seeds resulted from chromosome rather than chromatid changes, indicating that the chromosomes are single structures in cells of dormant seeds. In respect to frequency of translocations per spike, there was a uniform increase with rise in X-ray dosage through the 20,000 r treatment but no increase at dosages above 20,000 r. There were distinct differences in aberration frequencies induced by X-rays and neutrons in relation to plant survival. For an equal aberration frequency, thermal neutrons caused less seedling injury and death than X-rays. For example, 2 hours exposure to neutrons caused the same number of bridges per cell as 20,000 r of X-rays. Yet this neutron treatment did not cause any reduction in plant survival while the 20,000 r treatment caused death of plants. It was concluded that much of the injury from X-rays must be due to effects other than chromosome aberrations while the principal injury from neutrons is the result of chromosome breakage.

Several significant studies involving irradiation of dormant rice seed have been reported in recent years. Matsuo *et al.* (1958) and Yamaguchi (1958) found that plant survival and panicle fertility decreased linearly with increasing dosage of X-rays. Soriano (1959) reported that 20,000 γ and 25,000 γ dosages of gamma rays did not affect survival of seedlings but 30,000 γ and 40,000 γ treatments caused marked reductions and no surviving plants occurred following a 50,000 γ dose. Huang (1960) irradiated rice seeds with five doses of gamma rays ranging from 5,000 γ to 40,000 γ. In root tips the frequency of cells with aberrations increased linearly with dosage while the frequency of translocations in meiosis increased linearly up to 20,000 γ but remained constant between 20,000γ and 30,000 γ. From a comparison of root tip and PMC data, he concluded that there was strong elimination of cells containing chromosome aberrations at the highest dosages. Chao and Chai (1961) studied the effect of two X-ray dosages, 20,000 γ and 25,000 γ, on dormant seed of two rice varieties. Differences were found in response of the varieties. There was no significant reduction in seedling survival from 20,000γ but a reduction to about 70% of control from 25,000γ. The percentages of panicles containing translocations from the 20,000 γ and 25,000 γ dosages were 26 and 45 for one variety and 20 and 24 for the other variety. In a summary of research conducted in Japan dealing with irradiation of rice, Kawai (1962) reported that *japonica* varieties are generally more sensitive than *indica* varieties, the LD50 for *japonica* ranging from 20,000–50,000 γ and that for *indica* ranging from 20,000–65,000 γ.

Materials and Methods

Seeds, first generation seedlings and plants following irradiation of the cultivated rice variety Nato constituted the materials used in the study. Nato was developed by hybridization and includes germ plasm from both *japonica* and *indica* sources in its parentage.

Dormant seeds were treated with gamma rays from Co^{60} and fission neutrons at Oak Ridge, Tennessee by the University of Tennessee-Atomic Energy Commission Research Laboratory. Seed lots were irradiated in 1956 and 1957. In 1956, four dosages of gamma rays—15, 25, 35, and 40 Kr given at an intensity of 1,024 γ per minute were used while in 1957 gamma ray dosages of 20, 30, 40 and 50 Kr delivered at the rate of 775 γ per minute were obtained. Seed lots were exposed to neutrons for 1/4, 1/2, 1, 2 and 4 hours in 1956 and 1, 2, 3, 4 and 6 hours in 1957 at a rate of flux of 1.4×10^{12} thermal neutrons and 7.9×10^{10} fast neutrons per cm^2 per hour. Each year the seeds were sown in flats in the greenhouse shortly after irradiation and seedlings were transplanted to the field about 3 weeks after sowing.

Data were taken on number of seedlings emerged, height of the seedlings, number of plants surviving to maturity, degree of fertility of panicles on the R_1 plants and frequency of reciprocal translocations in panicles of R_1 generation plants. For the cytological studies individual panicles were collected while undergoing meiosis. An attempt was made to obtain 40–50 panicles from each radiation treatment. The panicles were fixed either in 3:1 alcohol-acetic acid or Newcomer's fixative.

Slides were prepared by the conventional aceto-carmine technique. Stages of meiosis studied were diakinesis and metaphase I, with a minimum of 50 PMC examined per panicle. If no multivalents indicative of translocations were found in the first floret examined, 2 or 3 additional florets from the panicle were checked in order to allow for the possibility that all florets of a panicle might not be identical.

Results

The effects of the gamma ray treatments during the two years on seedling emergence, plant survival, seedling height and fertility of the R_1 generation plants are presented in Table 1 and the results from the neutron treatments are given in Table 2.

Emergence and Survival of Seedlings

It is readily apparent from Table 1 that none of the gamma ray treatments in both years caused an appreciable reduction in emergence of seedlings in greenhouse flats. In respect to the neutron treatments, the results differed for the two years. In 1956, only the 4 hour dosage caused any reduction in emergence and this was small. But in 1957, with the same variety, moisture content of seed and neutron intensity, the 2 and 3 hour treatments caused small reductions in emergence, only about 10% of the seeds produced seedlings in the 4 hour treatment and no emergence occurred from the 6 hour treatment. There was no apparent explanation for the difference in effect of neutrons on emergence in the two years; however, variable results following irradiation of dormant seeds have been reported by many workers.

Laboratory experiments with reserve seed of the 1957 neutron treatments showed that all, including those exposed for 6 hours, were capable of germination. However, in the 4 and 6 hour treatments shoots did not develop beyond the coleoptile stage and the seedlings apparently did not go beyond the first mitotic division.

As shown in Tables 1 and 2, data on number of plants surviving to maturity were available only for the 1957 experiments. Unlike seedling emergence, even the lowest dosages of both gamma rays and neutrons caused detectable reductions in plant survival and percentage survival decreased with each increase in dosage. In the case of gamma rays, the reduction in survival resulting from increasing dosages was gradual and approximately linear, with a drop of about 10% for each increase of 10 Kr units. Survival following the 50 Kr treatment was about 50% of the control.

Table 1. *Effects from irradiation of dormant rice seeds with varying dosages of gamma rays on four characteristics of the R_1 generation.*

Year	Dosage (Kr)	Emergence (%)	Survival (%)	Seedling ht. (inches)	Fertility (%)
1956	0(Control)	93	—	4.2	—
	15	97	—	3.5	58.0
	25	92	—	3.3	27.9
	35	93	—	2.4	20.7
	40	90	—	2.3	19.1
1957	0(Control)	92	84	13.4	90.0
	20	92	74	11.3	52.0
	30	87	70	8.1	44.0
	40	87	59	9.0	31.0
	50	93	47	7.4	29.0

Table 2. *Effects from irradiation of dormant rice seeds with varying dosages of neutrons on four characteristics of the R_1 generation.*

Year	Dosage*	Emergence (%)	Survival (%)	Ave. Seedling Height (inches)	Fertility (%)
1956	0 (Control)	93	—	4.2	—
	1/4 hr.	96	—	4.3	69.8
	1/2 hr.	95	—	3.6	60.4
	1 hr.	92	—	3.1	57.1
	2 hrs.	96	—	3.5	35.8
	4 hrs.	81	—	2.5	0.0
1957	0 (Control)	83	83	13.04	90.0
	1 hr.	84	69	10.5	53.0
	2 hrs.	71	50	8.7	19.0
	3 hrs.	79	13	3.5	0 0
	4 hrs.	9	0	1.8	—
	6 hrs.	0	0	—	—

* The intensity of neutrons in both years was 1.4×10^{12} thermal neutrons per cm^2 per hour plus 7.9×10^{10} fast neutrons per cm^2 per hour.

The effects of increasing dosages of neutrons on survival was non-linear. The 1 hour treatment caused a moderate reduction, the 2 hour exposure caused a fairly sharp reduction and only about 10% of the original plants survived the 3 hour treatment.

In effects on survival, the 1 and 2 hour neutron treatments were comparable to 30 Kr and 50 Kr, respectively, of gamma rays. Three hours exposure to neutrons had a much more severe effect than any gamma ray dosage, reducing plant survival below a level that would be practical.

Seedling Height

Height records were taken at different ages in the two years, accounting for the greater height in 1957. In both years, all gamma ray dosages caused a significant reduction in seedling height. The reduction was gradual with increasing dosage and the effect seemed to be essentially linear with dosage.

As was the case for seedling emergence, the neutron effects in the two years were more variable. Whereas the reduction in height with increasing dosage was linear in 1957, all neutron treatments of more than 2 hours caused marked reductions in height in 1957.

An interesting difference between gamma rays and neutrons is also apparent in the relationship between seedling height and plant survival. The 30 Kr gamma ray and 1 hour neutron treatments had essentially the same survival but the seedlings in the neutron treatment were appreciably taller. A similar relationship held true for 50 Kr and 2 hours of neutrons. Both had about the same percentage survival but seedlings of the neutron treatment were taller. These results suggest that, in rice, neutrons when compared to gamma rays have a relatively high lethal effect on plants in relation to the effect on plant height.

Fertility of R_1 Plants

The effects of exposure of dormant seeds to gamma rays and neutrons on fertility of R_1 generation plants were determined by computing the percentage of florets which contained seed on 25 individual panicles per irradiation treatment. The results are presented in the last column of Tables 1 and 2.

Although data were not available from control plants in 1956, it can be assumed that the fertility of untreated plants would have been about the same as found in 1957 (90%). All treatments of both gamma rays and neutrons caused marked reductions in fertility. This was true even for the 1/4 hour neutron treatment although it had no effect on seedling height.

In case of the gamma rays, there was a decrease in fertility with increasing dosage up to approximately 35–40 Kr. However, in both years there was a distinct tendency for average fertility to reach a minimum and level off before the highest dosage had been reached. Thus, in 1956 there was no significant difference in fertility between the 35 and 50 Kr treatments and in 1957 between the 40 and 50 Kr dosages. Comparable gamma ray dosages of the higher level caused greater reductions in fertility in 1956 than in 1957. This is shown by the 40 Kr treatment, which had mean fertility of 10.1% and 29.0%, respectively, in the two years. This indicates an interaction between fertility level following irradiation and environment.

The neutron treatments caused increased reduction in fertility with increase in dosage. There was no tendency to reach a minimum and level off. In fact, during both years the highest neutron treatment that contained surviving plants reduced fertility to zero in all panicles. However, these plants involved were very late in heading due to the detrimental effects of the irradiation on plant development and it is probable that this late heading was a factor in the complete sterility of the plants.

Frequency of Translocations

Cultivated rice has a somatic chromosome number of 24. These regularly occur as 12 bivalents during diakinesis and metaphase of the first meiotic division. Consequently, the occurrence of multivalents at these stages in panicles derived from irradiated seeds was taken as evidence for one or more reciprocal translocations or interchanges induced by the irradiation treatments. Translocation frequencies for the various gamma ray dosages are presented separately for the two years in Table 3 and for the neutron treatments in Table 4. The gamma ray data are based on 38 to 50 panicles per treatment and the neutron data on 29 to 49 panicles of each treatment, except for the 3 hour neutron exposure where only 20 panicles could be collected.

Table 3. *Frequencies of translocations induced by varying dosages of gamma rays as indicated by multivalents in meiosis.*

Year	Dosage (kr)	No. Panicles Normal	No. panicles with following translocations				Mean translocations per panicle
			1	2	3	4	
1956	15	30	8	0	0	0	0.21
	25	26	11	1	1	0	0.45
	35	19	15	6	0	0	0.68
	40	30	8	1	1	2	0.50
1957	20	36	4	0	0	0	0.10
	30	23	16	1	0	0	0.45
	40	22	14	3	0	0	0.51
	50	28	17	4	1	0	0.56

In all gamma ray treatments, except for 35 Kr in 1956, more than 50% of the panicles were free of translocations. This indicates a relatively low translocation frequency in view of the unusually high dosages employed. However, translocations resulting in multivalents at meiosis represented only one of several types of aberrations induced by the irradiation.

As expected, the effects of the gamma rays in the two years were similar. Each year the higher dosages led to higher translocation frequencies than did the lower ones. However, the increase in translocation frequency with dosage was neither linear nor exponential. Instead, there was a distinct tendency for translocation frequency to reach a maximum at about 35–40 Kr and level off. The maximum translocation frequency from gamma rays was approximately 0.50–0.55 per panicle.

Table 4. *Frequencies of translocations induced by varying dosages of neutrons as indicated by multivalents in meiosis.*

Year	Dosage	No. Panicles Normal	No. panicles with following translocations			Mean translocations per panicle
			1	2	3	
1956	1/4 hr.	40	1	0	0	0.02
	2 hrs.	40	6	0	0	0.13
	4 hrs.	19	5	4	1	0.57
1957	1 hr.	37	3	0	0	0.07
	2 hrs.	40	6	3	0	0.24
	3 hrs.	6	11	3	0	0.85

Effect of the neutron dosages on translocation frequency was difficult to evaluate. Exposures below 2 hours cause very few aberrations. The 2 hour dosage had an effect comparable to 15–20 Kr of gamma rays. Due to poor plant survival, it was not possible to obtain enough panicles from treatments exceeding 2 hours for accurate measures of translocation frequencies. However, it is obvious that an increase with dosage occurred that was not linear.

Discussion

One of the most notable features of the results was the distinct tendency during both years of the study for the dosage-translocation frequency curve for the gamma ray treatments to level off at about 35–40 Kr. This phenomenon is apparently identical to the so-called "saturation effect" reported by McKey (1951) and Ehrenberg *et al.* (1953) following irradiation of dormant seed of barley with varying dosages of X-rays. The latter workers suggested that this saturation effect is due to the fact that the cells in the multicellular spike primordium of the dormant seed vary in sensitivity to radiation and, when the primordium is exposed to a high radiation dosage, the most sensitive cells, hence those having high aberration frequency, are killed and the spike develops from less sensitive cells.

The relative effects of gamma rays and neutrons on rice differed greatly from those reported for barley. Caldecott *et al.* (1952, 1954) found that for equal numbers of chromosome aberrations induced per cell, thermal neutrons caused less seedling injury than X-rays. The reverse was true for rice in the present studies. The 2 hour neutron treatment caused essentially the same translocation frequency as 15–20 Kr of gamma rays. This neutron dosage produced sharp reductions in plant survival and seedling height in contrast to the small effect on these traits by 20 Kr of gamma rays. It is apparent from the different results with barley and rice that each species is specific in response to ionizing radiations and general conclusions pertaining to plants cannot be drawn from experiments with one species. Due to the strong sensitivity to neutrons, it appears that gamma rays are more suitable for irradiation of rice.

Several lines of evidence obtained in the studies indicate that damage to plants of the R_1 generation by irradiation of dormant seed was not caused primarily by chromosome breakage. As pointed earlier, 20 Kr of gamma rays and the 2 hour neutron exposure appeared to cause similar degrees of chromosome aberration but the neutron treatment had more detrimental effects on plant survival and seedling height. Furthermore, the essentially linear relationship between gamma ray dosage and reduction in plant survival and seedling height in contrast to the plateau or saturation effect between dosage and translocation frequency also suggests that the damage is not due entirely chromosome breakage.

On the other hand, reduction in fertility was closely associated with translocation frequency in the gamma ray treatments, suggesting that the effect on fertility of surviving R_1 plants is due primarily to chromosome aberrations. However, all reduction in fertility could not be accounted for by the translocations found in the experiments. For example, in 1957 only 2 panicles of the 25 tested from the 50 Kr treatment were normal in fertility. Yet, 50% of the panicles from this treatment that were examined cytologically did not contain any transloctions. Most of the sterility not caused by transloctions was probably due to the presence of small deletions which had no detectable effect on plant survival and development in their "heterozygous" condition but caused abortion of spores and gametes following meiosis.

For all radiation treatments during the 2 years a total of 26 panicles were found which contained 2 translocations each, as evidence by the occurrence of a ring of 6 chromosomes or 2 rings of 4 chromosomes each. Since a ring of 6 is formed when the 2 interchanges involve only 3 chromosomes while 2 rings of 4 indicate that 4 chromosomes were involved, determination of the relative frequencies of the 2 types can be made. Fourteen panicles had a ring of 6 and 12 had 2 rings of 4 chromosomes. Apparently the 12 pairs of chromosomes in rice are not equally likely to be involved in translocations. Instead certain of the chromosomes have a high frequency of 2 breaks while others have a low frequency of single breaks since, if breaks occur in 2 chromosomes to form a single translocation, there is an equal tendency for a second set of breaks to involve one of the same 2 chromosomes as one of the other 10 pairs.

The experiments provide considerable information concerning the choice of type of radiation and appropriate dosage for use in induction of beneficial mutations. The use of neutron irradiation has several disadvantages and, since rice proved more sensitive to neutrons than to gamma rays, it appears that gamma radiation is preferable for dormant seed of rice. If the assumption is made that the mutation rate increases with dosage, an assumption for which there is not proof as yet, the results of the present experiments indicate that gamma ray dosages of 40 to 50 Kr can be utilized safely on dormant rice seed. (Later experiments have shown that moisture content of the dormant rice seed has a marked influence on plant survival and development. Plant survival of 50% following a dosage of 50 Kr occurs only when the moisture content of the dormant seed is within the range of 13–15%. Dosages above 50 Kr usually reduce survival below 50% regardless of moisture content).

Summary

All doses of gamma rays ranging from 15 Kr to 50 Kr caused measureable reductions in survival of R_1 plants. The reduction with increasing dosage was linear, with a drop of about 10% for each increase of 10 Kr.

Dormant seed of rice proved highly sensitive to neutron radiation. Consequently, neutron radiation cannot be recommended for induction of mutations in rice.

All treatments of both gamma rays and neutrons caused marked reductions in fertility. However, the dosage-fertility curve was not linear for gamma rays as there was a distinct tendency for fertility to reach a minimum and level off before the highest dosage was reached.

The same so-called "saturation effect" was found for the gamma ray treatments on frequency of translocations. The translocation frequency reached a maximum at about 35–40 Kr and did not increase further from 50 Kr.

Several lines of evidence indicated that damage to R_1 plants by irradiation of dormant seed was not caused primarily by chromosome breakage.

Because of major differences in results obtained here with rice and those

reported with barley, it is apparent that general conclusions concerning response of various economic plants to irradiation of dormant seed connot be drawn from research with a single or a few species.

Due to a relatively high frequency of rings of 6 chromosomes compared to 2 rings of 4 chromosomes, it was concluded that certain of the 12 pairs of rice chromosomes undergo breakage much more frequently than do others.

The results indicated that gamma ray dosages of 40–50 Kr can be utilized with dormant seed of rice, provided the moisture content of the seed is within the range 13–15%.

以 γ-ray 中子處理水稻休眠種子對於其 R_1 植物的若干影響

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作者等以 Co^{60} 發出的 γ-ray 及中子處理水稻品種 Nato 的休眠種子。供處理用的 γ-ray 的量，1956年是分 15, 25, 35, 40 Kr 四區，1957年是分 20, 30, 40, 50 Kr 四區，每年皆設不受處理者爲對照區。供處理用的中子，1956年是分 ¼, ½, 1, 2, 4 小時等五區，1957年是分 1, 2, 3, 4, 6 小時等五區，中子流量是每小時每平方公分爲 1.4×10^{12} 的 thermal neutrons 和 7.9×10^{10} fast neutrons。每年亦皆設不受處理的對照區。處理後的調查項目是發芽數、殘存數、苗的高度及結實率等四項，同時亦檢視生存者減數分裂時的染色體行爲。

1. 作者等實驗的結果，見在 15—50 Kr 範圍中的 γ-ray 使受處理種子的第一代 (R_1) 植物的生存率降低，在此範圍中，γ-ray 的量每增 10 Kr，R_1 植物的生存率是隨着降低 10%。

2. 休眠種子對於中子的放射線甚爲敏感，但中子並不是一個引起突變的良好的放射線源。

3. γ-ray 與中子的處理，皆使 R_1 植物的結實率降低，但 γ-ray 的量與結實率間的關係，並不是一直線。即結實率降低至某一限度，γ-ray 的量縱令增加，結實率亦不復降低。

4. γ-ray 有引起染色體斷片轉位 (translocation) 的作用，而亦有所謂"飽和效果"。即 γ-ray 量達 35—40 Kr 時，轉位的次數(frequency)達於最高，但 γ-ray 的量縱令高至 50 Kr，轉位次數不復增加。

5. 染色體斷片轉位的結果，造成一個六染色體的環或二個四染色體的環者頗多。故在水稻的 12 對染色體中，似有若干對染色體是比較易於裂斷。

6. R_1 植物所受放射線之害，其直接原因似不是由於染色體之裂斷。

7. γ-ray 的效果與休眠種子的含水量間有關係，種子含水量爲 13—15% 時，γ-ray 的量用至 40～50 Kr，約有50% R_1 植物可以生存。(摘要)

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