Identification of Irradiated Potatoes by Impedance Measurements

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Measuring the impedance was found to be a highly reliable and practical technique for identifying irradiated potatoes. Impedance was measured by puncturing a potato tuber with a steel electrode and passing a 3~5 mA alternating current through it. Three parameters were determined: Z_0/Z_{180} (impedance ratio at 5 kHz, 0 to 180 seconds after puncturing), $Z_{50k}/Z_{0.5k}$ (impedance ratio at 50 kHz to 0.5 kHz) and Z_{50k}/Z_{5k} (impedance ratio at 50 kHz to 5 kHz). Among these, parameter Z_{50k}/Z_{5k} was the most favourable index. The technique allowed not only differentiation between unirradiated and irradiated potatoes but an estimation of the irradiation dose for up to six months after irradiation, independent of the potato storage condition.

Irradiated potatoes are accepted unconditionally by the international authorities^{1~2)} (IAEA, WHO and FAO) and permitted in various countries³⁾ in the world. In Japan commercial potato irradiation with Co-60 on a larger scale has been performed in order to inhibit sprouting since 1973. Every year around 20000 t of potatoes (Danshaku) are irradiated with a dose of 7 to 15 krad. Although the wholesomeness of irradiated potatoes has already been confirmed,^{1,2)} some consumers are against them and are interested in a reliable method to differentiate between unirradiated potatoes and irradiated ones. The technique to identify irradiated potatoes should be dependent upon the irradiation dose but not on other conditions for storage, growth *etc.* Such a technique is also required at an irradiation plant to avoid re-irradiation.

A reliable technique to identify irradiated potatoes has not so far been established, although several methods have been reported.^{4~14)} Most of these dealt with enzyme activities,^{7,9)} or with the amount of potato components^{4,8)} like carbohydrates, amino acids, vitamins and chlorogenic acid, which all changed during storage and were influenced by the storage and growth conditions and by the

potato varieties.

The technique of measuring the electrical conductivity of potatoes has been reported^{10~14)} to be promising for this identification. The conductivity is measured by puncturing a potato tuber with an electrode and passing alternating current through it. The process is quite simple, takes only 3 minutes and does not require a trained operator. Irradiation lowers the electrical conductivity of potatoes measured immediately after puncturing with an electrode. After puncturing the conductivity continues to decrease for a few minutes depending on the irradiation dose. These effects are independent of the type of irradiation used for sprout inhibition. Scherz^{10~12)} measured the electrical conductivity at 50 Hz and concluded that A_0 (electrical conductivity immediately after puncturing) changed depending on the potato sample and A_{30} - A_{180} (or A_0 - A_{180}) was a better identification parameter, where A_t is the electrical conductivity of potatoes t seconds after puncturing. Hayashi and Ehlermann¹⁴⁾ improved the technique; an alternating current frequency of 5 kHz and a steel electrode gave the best results and the parameter of A_{180}/A_{30} (or A_{180}/A_0) was best suited for the identification.

Despite this improvement, the conductivity measurement did not result in a reliable identification, because the parameter of A_{180}/A_{30} was still unstable during storage after irradiation.

Impedance has been reported^{15~19)} to be dependent on the physiological conditions of plants, and winter hardiness of tree seedlings,^{15,18)} virus infection of plants¹⁷⁾ and the effectiveness of herbicides¹⁶⁾ have all been investigated by impedance measurement. In these investigations a ratio of impedance at low frequency to that at high frequency proved of higher significance than an impedance value itself.

In this report, the measurement conditions of impedance were investigated. Several identification parameters of impedances at low frequency, an impedance ratio at 0 to 180 sec after puncturing with the electrode and impedance ratios of low frequency to high frequency were compared using a large number of potatoes.

MATERIALS AND METHODS

Potato. Unless otherwise stated, the potato variety of Danshaku was used for this study, since potatoes of this variety are commercially irradiated in Japan. The potatoes were obtained from Shihoro Agricultural Co-operative, where commercial irradiation of potatoes is conducted. Potatoes of the variety May-Queen were obtained from a local market in Tsukuba, Ibaraki-ken.

Irradiation. Potatoes were irradiated with a dose of 0 to

100 krad using a Gamma Cell 220 (Canada AEC, Co-60, 288 krad/hr). The accuracy of the irradiation dose rate was within $\pm 15\%$. After irradiation, the potatoes were stored at 5 or 15°C in a dark room.

Impedance measurement. Prior to the experiments, the potatoes were adjusted to 20°C and the electrical measurements were carried out at that temperature with the aid of stainless-steel electrodes; 1 mm diameter, 1 cm long and 1 cm apart (Fig. 1). The impedance was determined by puncturing a potato tuber with the electrodes which were connected to a Vector Impedance Meter 4800 A (Hewlett Packard Ltd.), and expressed as follows. Z_x , impedance measured x sec after puncturing; Z_{yk} , impedance at y kHz measured immediately after puncturing.

RESULTS AND DISCUSSION

Impedance at various frequencies

Potatoes were irradiated with a dose of 0, 15, or 100 krad and stored at 15°C for 1 week. Their impedance was measured at 20°C at various frequencies of alternating current. Each point in Fig. 2 is an average of 10 measurements in 5 potatoes measured immediately after puncturing with the electrodes. In the low frequency range the impedances were different depending on the irradiation dose, but at higher frequencies this difference could not be observed. These results suggested the suitability of impedance measurement at low frequency as a tool for identification. But Scherz^{10~12)} reported that the electrical conductivity at 50 Hz was rather scattered and would not be a stable parameter.

As described above, the ratio of impedance at low frequency to that at high frequency has

FIG. 1. Diagram of the Steel Electrodes Used in Measuring the Impedance of a Potato Tuber.

FIG. 2. Impedance of Potatoes at Various Frequencies of Alternating Current.

○, 0 krad; ●, 15 krad; ■, 100 krad.

been recommended for use as a parameter for the diagnosis of plants,^{15~19)} and this seemed to be worth trying as a parameter for the identification of irradiated potatoes. In this study the ratio of impedance at 50 kHz to that at 0.5 kHz ($Z_{50k}/Z_{0.5k}$) and the ratio of impedance at 50 kHz to that at 5 kHz (Z_{50k}/Z_{5k}) were used as identification parameters.

Changes in impedance after puncturing with the electrodes

Potatoes were irradiated with a dose of 0, 15 or 100 krad and stored at 15°C for 1 week. Their impedance at 5 kHz was measured at 20°C. The impedance measurement was done at intervals after puncturing the potato sample with the electrodes by keeping them in the tuber. Each point in Fig. 3 is an average of 10 measurements in 5 potatoes. The impedance of unirradiated potatoes kept increasing with the time after puncturing, whereas at 15 krad the impedance was almost constant and at 100 krad it kept decreasing. These results sug-

FIG. 3. Impedance Change at 5 kHz after Puncturing a Potato Tuber.

○, 0 krad; ●, 15 krad; ■, 100 krad.

gested that the impedance change after puncturing with the electrodes would be promising for the identification of irradiated potatoes. Although the applicability of A_{180}/A_0 has been already investigated,¹⁴⁾ the ratio of the impedance 0 second to that 180 seconds after puncturing (Z_0/Z_{180}) seemed to be a better parameter to compare with the parameters of $Z_{50k}/Z_{0.5k}$ and Z_{50}/Z_{5k} .

Relationship between the identification parameter, Z_0/Z_{180} , and the frequency of alternating current

Potatoes were irradiated with a dose of 0 to 100 krad and stored at 15°C for 1 week. Their impedance was measured at 20°C at various frequencies of alternating current to determine Z_0/Z_{180} . As shown in Fig. 4, Z_0/Z_{180} increased as the irradiation dose increased in the frequency range of 50 Hz to 10 kHz, but this effect was not observed at 50 kHz, where the mean values and the standard deviations were determined with 6 measurements in 6 potatoes. In order to establish the best frequency for the

FIG. 4. Relationship between the Identification Parameter, Z_0/Z_{180} , at 20°C and the Frequency of Alternating Current.

○, 0 krad; ●, 5 krad; □, 10 krad; ■, 15 krad; △, 20 krad; ▲, 30 krad; ▽, 50 krad; ▼, 100 krad.

TABLE I. VARIANCE RATIO ($V_R/V_e = F$) OF IDENTIFICATION PARAMETER, Z_0/Z_{180} , DETERMINED AT VARIOUS FREQUENCIES OF ALTERNATING CURRENT

Frequency (Hz)	50	100	500	1 k	5 k	10 k	50 k
F	8.38	18.48	8.44	11.55	60.01	24.73	1.27
n	48	48	48	48	48	48	48

parameter of Z_0/Z_{180} , the variance ratio ($V_R/V_e = F$) of the results was calculated (Table I). The frequency of 5 kHz produced the highest F -value, which indicated that this frequency was best suited for identification when the parameter of Z_0/Z_{180} was used. This result agreed with that of the previous paper,¹⁴ where A_{180}/A_0 was used as a parameter and the best frequency of 5 kHz was obtained from the results of 5 weeks' measurements.

Measuring temperature

Potatoes of Danshaku and May-Queen were irradiated with a dose of 0, 20 or 100 krad and stored at 15°C for 1 week. Their impedance was measured at various temperatures. The parameters of Z_0/Z_{180} , $Z_{50k}/Z_{0.5k}$ and Z_{50k}/Z_{5k} were determined at each temperature. At 5°C the differentiation between unirradiated potatoes and irradiated ones was possible but the estimation of the irradiation dose was impossible as shown in Figs. 5 to 7, where the mean values and the standard deviations were determined with 10 measurements in 5 potatoes. In the temperature range of 20 to 35°C

each parameter depended on the irradiation dose, which indicated the possibility of estimation of the irradiation dose as well as differentiation between unirradiated and irradiated potatoes. Higher temperatures, however, resulted in poorer identification. The

FIG. 5. Relationship between the Identification Parameter, Z_0/Z_{180} , at 5 kHz and the Measuring Temperature.

○, 0 krad; ●, 20 krad; ■, 100 krad.

FIG. 6. Relationship between the Identification Parameter, $Z_{50k}/Z_{0.5k}$, and the Measuring Temperature.

○, 0 krad; ●, 20 krad; ■, 100 krad.

FIG. 7. Relationship between the Identification Parameter, Z_{50k}/Z_{5k} , and the Measuring Temperature.

○, 0 krad; ●, 20 krad; ■, 100 krad.

TABLE II. VARIANCE RATIO ($V_R/V_e = F$) OF IDENTIFICATION PARAMETERS DETERMINED AT VARIOUS TEMPERATURES FOR POTATOES IRRADIATED WITH A DOSE OF 0, 20 OR 100 krad

(A) May-Queen

Parameter	Temp. (°C)					
	5	20	30	35	40	50
$Z_{0.5k}$	58.6	198.3	174.2	97.6	161.4	154.3
$Z_{50k}/Z_{0.5k}$	127.6	202.6	196.3	175.7	86.8	140.9
Z_{5k}	49.5	79.9	113.8	93.9	71.9	94.1
Z_{50k}/Z_{5k}	203.1	368.5	185.5	209.0	43.0	260.1
Z_{50k}	4.5	7.6	4.5	0.4	3.5	3.1
Z_0/Z_{180}	52.0	285.1	49.8	81.9	20.6	10.5

(B) Danshaku

Parameter	Temp. (°C)					
	5	20	30	35	40	50
$Z_{0.5k}$	75.5	91.5	139.5	55.4	33.2	21.9
$Z_{50k}/Z_{0.5k}$	210.4	265.2	200.1	203.9	49.4	32.3
Z_{5k}	94.9	75.0	104.4	76.4	20.1	36.2
Z_{50k}/Z_{5k}	341.7	294.8	309.4	117.4	57.6	50.5
Z_{50k}	3.1	5.1	20.6	1.6	11.3	1.6
Z_0/Z_{180}	100.7	256.4	81.6	240.6	254.8	4.2

variance ratio (F -value) of the results was calculated to establish the best conditions for identification (Table II), where Z_{50k} , Z_{5k} and $Z_{0.5k}$ were also subjected to calculation.

The normalized parameters of $Z_{50k}/Z_{0.5k}$ and Z_{50k}/Z_{5k} produced higher F -values than $Z_{0.5k}$, Z_{5k} and Z_{50k} , which indicated that the normalization might lead to better identification. These results proved the validity of using $Z_{50k}/Z_{0.5k}$ and Z_{50k}/Z_{5k} instead of $Z_{0.5k}$ and Z_{5k} (see the section "*Impedance at various frequencies*"). A measuring temperature of 20°C produced the highest F -values for $Z_{50k}/Z_{0.5k}$, Z_{50k}/Z_{5k} and Z_0/Z_{180} with May-Queen. With Danshaku a measuring temperature of 20°C did not always produce the highest F -values for the parameters but did produce consistently high F -values. From these results a measuring temperature of 20°C was concluded to be best suited for the identification of irradiated potatoes.

Identification during a long storage

Potatoes of Danshaku were irradiated with a dose of 0 to 100 krad and stored at 5°C or 15°C in a dark room. The impedance of the potatoes was measured at 20°C periodically for 6 months. The results were shown in Figs. 8 to 13, where the mean values and the standard deviations were determined with 10 measurements in 5 potato tubers. When stored at 15°C, the unirradiated potatoes started sprouting in 40 days (indicated with an arrow in Figs. 9, 11 and 13) and in the 4th month their sprouts were longer than 10 cm, so the impedance measurement was ceased thereafter. Although the parameter of Z_0/Z_{180} changed during storage, the parameters of $Z_{50k}/Z_{0.5k}$ and Z_{50k}/Z_{5k} stayed constant during storage after irradiation. The two parameters were dependent on the irradiation dose but independent of the storage temperature. The parameter of $Z_{50k}/Z_{0.5k}$ scattered more than Z_{50k}/Z_{5k} , which was confirmed from the F -values in Table III. The mean values, standard deviations and F -values

FIG. 8. Identification Parameter, Z_0/Z_{180} , at 5 kHz for the Potatoes Stored at 5°C.

○, 0 krad; ●, 5 krad; □, 10 krad; ■, 15 krad; △, 20 krad; ▲, 30 krad; ▽, 50 krad; ▼, 100 krad.

FIG. 9. Identification Parameter, Z_0/Z_{180} , at 5 kHz for the Potatoes Stored at 15°C.

○, 0 krad; ●, 5 krad; □, 10 krad; ■, 15 krad; △, 20 krad; ▲, 30 krad; ▽, 50 krad; ▼, 100 krad.

in Table III were determined with all the data from 6 months' measurements.

The parameter of Z_{50k}/Z_{5k} at 20°C was concluded to be the best index for the identi-

FIG. 10. Identification Parameter, $Z_{50k}/Z_{0.5k}$, for the Potatoes Stored at 5°C.

○, 0 krad; ●, 5 krad; □, 10 krad; ■, 15 krad; △, 20 krad, ▲, 30 krad, ▽, 50 krad, ▼, 100 krad.

FIG. 11. Identification Parameter, $Z_{50k}/Z_{0.5k}$, for the Potatoes Stored at 15°C.

○, 0 krad; ●, 5 krad; □, 10 krad; ■, 15 krad; △, 20 krad; ▲, 30 krad; ▽, 50 krad, ▼, 100 krad.

cation of irradiated potatoes; roughly speaking, unirradiated potatoes will give a value of 0.43 to 0.36, potatoes irradiated with the legally admitted dose (7 to 15 krad) will give a value of 0.35 to 0.29 and potatoes irradiated with a dose exceeding the admitted level will give a value lower than 0.29 (Table III). These criteria were independent of storage tempera-

FIG. 12. Identification Parameter, Z_{50k}/Z_{5k} , for the Potatoes Stored at 5°C.

○, 0 krad; ●, 5 krad; □, 10 krad; ■, 15 krad; △, 20 krad; ▲, 30 krad; ▽, 50 krad; ▼, 100 krad.

FIG. 13. Identification Parameter, Z_{50k}/Z_{5k} , for the Potatoes Stored at 15°C.

○, 0 krad; ●, 5 krad; □, 10 krad; ■, 15 krad; △, 20 krad; ▲, 30 krad; ▽, 50 krad; ▼, 100 krad.

TABLE III. RELATIONSHIP BETWEEN IDENTIFICATION PARAMETERS AND IRRADIATION DOSE FOR POTATOES OF DANSHAKU VARIETY

Dose (krad)	Parameter		
	Z_0/Z_{180}	$Z_{50k}/Z_{0.5k}$	Z_{50k}/Z_{5k}
0	0.907 ± 0.030	0.298 ± 0.025	0.392 ± 0.022
5	0.956 ± 0.021	0.260 ± 0.021	0.346 ± 0.018
10	0.971 ± 0.023	0.247 ± 0.017	0.328 ± 0.017
15	0.983 ± 0.023	0.229 ± 0.021	0.310 ± 0.019
20	0.997 ± 0.022	0.209 ± 0.023	0.290 ± 0.020
30	1.007 ± 0.023	0.182 ± 0.030	0.269 ± 0.021
50	1.024 ± 0.024	0.158 ± 0.025	0.250 ± 0.018
100	1.045 ± 0.023	0.129 ± 0.026	0.225 ± 0.017
F-Value	450.0	778.6	1108.3
n	1250	1250	1250

ture and were valid up to 6th month after irradiation, the longest storage period tested.

It could be concluded that impedance measurement was a highly reliable and practical technique for the identification of irradiated potatoes, which facilitated not only the differentiation between unirradiated potatoes and irradiated ones but also the estimation of irradiation dose. Further study would be necessary to examine the applicability of the above criteria to potatoes other than Danshaku.

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