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Effect of repetitive impacts on subcutaneous tissue discolouration in potato tubers

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Abstract

From field to shop, table potatoes are exposed to many mechanical forces (impacts) and are probably impacted often at the same site. We investigated the relation between one or more doses of impact energy delivered at one tuber site and the resulting volume and depth of discoloured tissue. Tubers were impacted at a desired rate with a computer-controlled pendulum. The tubers were from plants grown at 2 potassium levels (*i.e.* susceptibilities to tissue discolouration) and stored for 3, 5 or 7 months.

Splitting of the impact energy into various (up to 9) doses reduced the volume of discoloured tissue by up to 64%. The depth of tissue damage was less affected (33% reduction) by splitting the impact energy than the volume was. The volume and depth of discoloured tissue increased with the number of 0.3 J impacts. A decreasing and an increasing order of impact energy caused the same tissue damage.

Despite the experimental simplification and standardization the observed effect of the energy and frequency of impacts on the degree of subcutaneous tissue discolouration yielded relevant suggestions for practical potato handling.

Keywords: *Solanum tuberosum* L., table potato, impact, internal damage, bruising, blackspot, discolouration, handling, pendulum

Introduction

In the chain of handling operations, from the field to the shop, table potatoes are exposed to mechanical forces (impacts). In the average Dutch handling chain a single potato is impacted 340 times and experiences 72 drops exceeding 10 cm (Molema & Bouman, 1996). Drops and changes in speed and direction are caused by conveyor belts and other links in the chain, and by tuber to tuber contacts. Tubers may be impacted several times at the same site. Repetitive impacts on the same site may be caused by the position of the centre of gravity in a tuber, which is usually eccentric.

Impacts can lead to different types of damage. An important one is subcutaneous tissue discolouration, which mostly occurs at relatively low impact energies (Parke,

1963). Tissue discolouration, bruising, blackspot, tissue damage and other terms, though usually poorly defined, are often used to describe approximately the same phenomenon (see definition in Materials and methods).

The relation between the number of doses of impact energy at a tuber site and the resulting volume and depth of discoloured tissue is not known and was therefore investigated. The present work addresses three questions:

- Is there a difference in volume and depth of discoloured tissue when the same site is impacted with a certain amount of energy applied either in one dose or divided over several doses? (Experiment 1)
- What is the relationship between the number of impacts and the volume and depth of discoloured tissue? (Experiment 2)
- What is the effect of a series of impacts, either in a decreasing or an increasing order of magnitude of energy, on the volume and depth of discoloured tissue? (Experiment 3)

To study the effect of impacts on tissue discolouration an instrument is needed to control the delivery of energy. For this purpose a pendulum was chosen (Grant & Hughes, 1985; Noble, 1985; Skrobacki *et al.*, 1989).

Materials and methods

Growing and storage of the tubers

The potatoes (*Solanum tuberosum* L., cv. Bintje grade 50–60 mm) were produced on a sandy soil (10% < 16 μm) in Slootdorp (Wieringermeerpolder, NL) under the usual regime for table potatoes in the Netherlands: planting in April, harvest after *ca* 160 d in October and chemical haulm killing three weeks prior to harvest. The plants were given a low (K1) or a high (K2) level of potassium fertilizer to induce differences in susceptibility to tissue discolouration. The tubers were harvested manually and stored individually on soft ventilating pads to minimize mechanical damage. The tubers of the K1 and K2 plots were randomly distributed over 3 groups and transferred to a cold store in which they were cooled from 15 to 4.5 °C (at 93% RH) in 2 weeks. This treatment was long enough to allow suberization and to maintain dormancy. Three, five or seven months after harvest the three groups of potatoes were removed from the cold store for pendulum experiments.

The pendulum

A computer-controlled pendulum was designed and constructed (Figure 1) to impact tubers at a desired rate. The impact energy is determined by the initial angle (α) of the pendulum, the weight of the pendulum arm and the impact body, the shape of the pendulum arm and the impact body, the mainframe-pendulum friction and the air resistance. The angle α could be varied to simulate different drops that average tubers of grade 50–60 mm (*ca* 120 g FW) undergo in practice. In the current experiments a spherical impact body (radius of curvature 30 mm, diameter 30 mm) was used. The

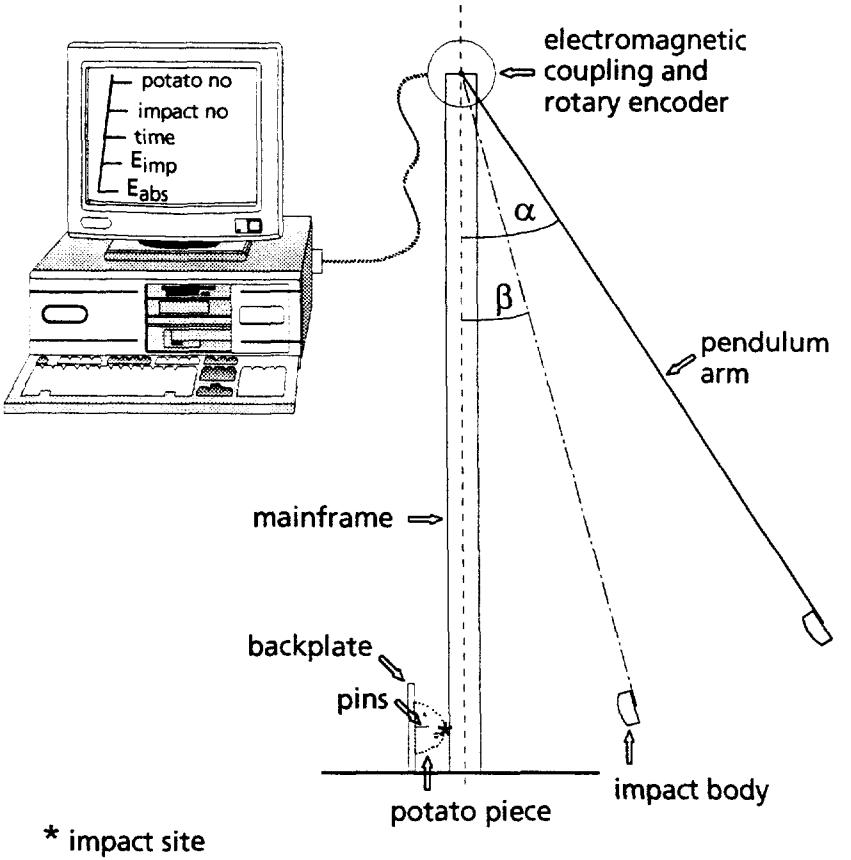

Figure 1. Schematic representation of the pendulum device.

computer programme compensates for energy losses due to friction at the main-frame-pendulum joint and for air resistance to calculate the angle corresponding with the selected amount of impact energy. An electromagnetic coupling kept the pendulum in its desired position until it was released by a computer command. When the pendulum had come to a standstill after the impact, it was automatically arrested. The rebound angle (β) was assessed as a measure of the non-absorbed energy. Both given and non-absorbed energy were measured with an accuracy of ± 2 mJ.

Preparation of the tubers

For our experiments potatoes were cut longitudinally into pieces with a maximum thickness of 30 ± 2 mm. Cutting into pieces allowed a stable positioning of the flat back of the pieces to the backplate of the pendulum by means of two pins (extending 12 mm, diameter 1 mm). Finney (1963) found no difference in the effect of impacts

between whole and halved tubers. The tuber pieces were impacted on a site perpendicular to the middle of the distance between rose and heel end (s.d. = 10 mm). A defined impact location was chosen to avoid the interference of differences in tissue properties, such as those reported by Corsini *et al.* (1992). Before impact treatments, the tubers were brushed carefully to remove adhering soil. For each individual impact experiment, the weight, length, maximum width and width perpendicular to maximum width of the whole potato and of the impacted piece were recorded. The impact site was marked and its radius of curvature was measured lengthwise and broadwise. On the assumption that the surface of the impact site is part of a spherical object, the curvature was measured with a set of templates with known curvatures. Curvature was expressed as the radius of the corresponding circle.

Experiments

An impact energy of 0.6 J was taken as a standard and included in all experiments. This energy level corresponds to a drop of an average tuber (grade 50–60 mm) of *ca* 50 cm, which occurs frequently in practice (Molema *et al.*, 1995) and did not cause external damage. Repetitive impacts were exerted on the same impact site. The time between consecutive impacts was *ca* 10 s. Per treatment (combination of impact type, potassium level and storage period) 45 tubers were impacted. All experiments were done at 10 °C and the tubers were transferred to 10 °C and 93% RH *ca* 1 week prior to impact experiments. After impact the tuber pieces were stored at 20 °C for 4 days according to the protocol described in Molema *et al.* (1995).

The following experiments were done:

Experiment 1: the impact energy (0.6 J) was divided over 1, 3, 6 or 9 impacts.
Experiment 2: the number of 0.3 J impacts was 1, 2, 4 or 8.
Experiment 3: a series of impacts (0.6, 0.2 and 0.067 J) was given in either a decreasing or an increasing order of magnitude of energy.

Four days after the impacts the volume and depth of the discoloured tissue were determined. The experiments were done with tubers stored for 3, 5 or 7 months (referred to as 3M, 5M and 7M, respectively). Due to difference in storage periods and the time lapse between experiments with tubers from one storage period, the absolute values of tissue discolouration may vary from one experiment to another.

Assays

At harvest and at the start of experiments the dry matter content (calculated from under-water weight as reported by Rastovski *et al.*, 1987) and the susceptibility to tissue discolouration were determined in the tubers as described by Molema *et al.* (1995). To assess subcutaneous tissue discolouration the pieces were sliced (average thickness 1.5 mm) with a calibrated peeler. The volume and depth of the discoloured tissue were calculated by measuring the surface of discoloured tissue in consecutive slices on an illuminated glass plate (Figure 2) and by adding up the number of slices with discoloured tissue. The cross sections of the discoloured tissue were predomi-

nantly ellipsoid, as observed earlier by Noble (1985). The length and width of the ellipses were used to calculate the surface of the discoloured tissue.

Note: in this article tissue discolouration encompasses all blue and blue-grey deviation in tissue colour relative to the surrounding tissue.

Statistical analysis

Volume of discoloured tissue

The tubers were divided into 11 classes. Tubers without visible discolouration belonged to class 1, the other tubers to ten sequential classes according to their volume of discoloured tissue. Tubers were divided over classes in such a way that added up over all 3 experiments every class consisted of nearly the same number of tubers. For the analysis of a classified response variable a multinomial distribution was assumed for the observed number of tubers per class. Since the multinomial distribution differs from a normal distribution, a generalized linear model was used (McCullagh & Nelder, 1989). A logistic function was used as link function. Due to the use of a link function a linear equation can be used on the transformed scale. The model equation used was:

$$\log\left(\frac{\gamma_i}{1-\gamma_i}\right) = \sum\theta_i + Xb + Zu \qquad (1)$$

in which γ_i is the cumulative probability to be in class i or a lower class; θ_i is the upper limit of each class (at the transformed scale) and b is the vector with fixed ef-

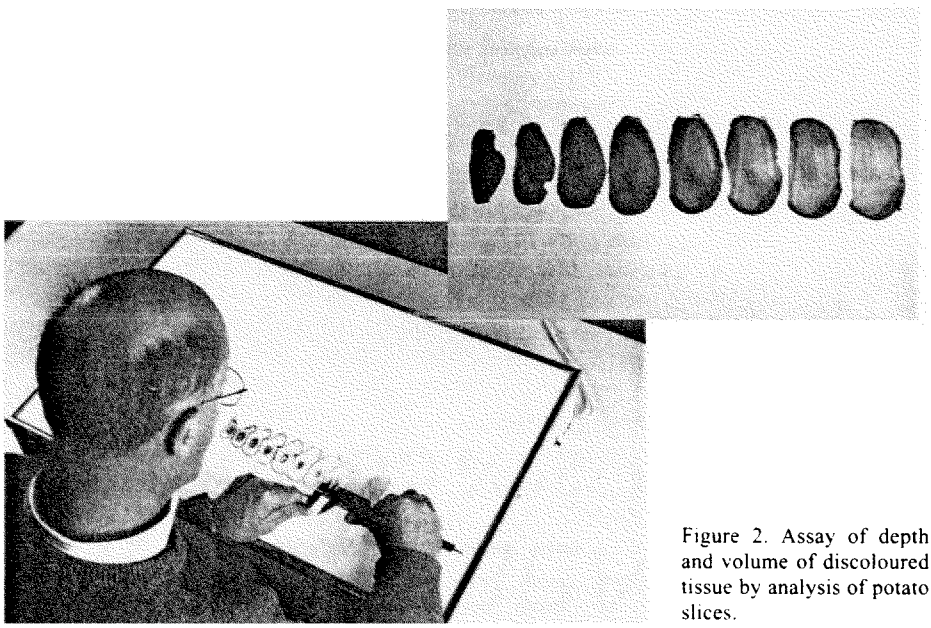

Figure 2. Assay of depth and volume of discoloured tissue by analysis of potato slices.

fects belonging to the design matrix X; u is the vector with random effects and Z the design matrix belonging to u. The latter term makes the equation (1) different from a generalized linear equation which results in a generalized linear mixed model (Engel & Keen, 1994).

With the procedure CLASS (Keen, 1994) belonging to the statistical package Genstat (Payne *et al.*, 1993), the data were analysed. The 3-factor interaction consisting of the terms impact treatment, storage duration and susceptibility to tissue discolouration was used as a random term. This term had a large effect on the volume of discoloured tissue. Moreover all the main effects and 2-factor interactions (combinations of the factors plot, treatment, storage duration and susceptibility to discolouration) were analysed.

Depth of discoloured tissue

The depth of discoloured tissue is a non-negative number. It was expected that the variation of this parameter depended on the expected value of depth. Therefore a generalised linear model was used and a Poisson-distribution was assumed for the depth of discoloured tissue. A logarithmic function was used as link function. By using a link function the effects were supposed to be multiplicative. This indicates that only proportional effects of the different factors were taken into account. The model used was:

$$\log(y) = Xb \qquad (2)$$

in which y is the depth of discoloured tissue. These depth data were analysed with the statistical package Genstat.

The effects of the covariates specific gravity, surface of the flat back of the tuber piece and the curvature lengthwise and broadwise of the tuber on the volume and depth of discoloured tissue were also analysed. In all experiments the effects of these covariates on the depth and volume of discoloured tissue were not significant. In the tables the mean experimental data are presented, while the statistical analyses were done on values predicted by the described models.

Results

At the onset of the experiments the tubers were free of tissue discolouration. K1 tubers contained *ca* 2% more DM than K2 tubers (Table 1). The susceptibility index for discolouration was positively correlated with the dry matter content. Susceptibility increased during storage up to 5 months, but fell after seven months (Table 1). The average fresh weight (125 ± 29 g), dimensions (length 82 ± 10 mm, width 55 ± 4 mm) and radius of curvature of the impact site (r = 54 ± 18 mm lengthwise and 19 ± 3 mm broadwise) were neither affected by storage, nor by the potassium treatment (data not shown). The potato pieces had an average weight of 68 ± 12 g (FW), a length of 82 ± 11 mm, a width (perpendicular to the maximum width of the whole tuber) of 45 ± 4 mm and the impact site 30 ± 2 mm from the backplate of the pendulum device. Over all experiments, the tubers absorbed *ca* 70 to 80% of the en-

Table 1. Dry matter content and susceptibility to discolouration in tubers grown at 2 potassium levels (K1, K2) and stored for 0, 3, 5 or 7 months (0, 3, 5, 7M).

Storage period	Dry matter content (%)		Susceptibility to discolouration (index)	
	K1	K2	K1	K2
0M	23.5	21.6	27	12
3M	24.1	22.0	30	15
5M	24.4	22.1	34	25
7M	24.1	21.9	21	14

Table 2. Impact energy (E_{imp}) and absorbed energy (E_{abs}) in tubers of the three experiments. Tubers were stored for 3, 5 or 7 months (3, 5, 7M). The impact treatments per experiment are given as the number of impacts times the given doses. In Experiment 3 single doses were given consecutively. All energies in J.

Experiment	Treatment (E_{imp}) (J)	E_{abs} (J)		
		3M	5M	7M
1	*1 x 0.600*	0.50	0.50	0.50
	3 x 0.200	0.45	0.44	0.45
	6 x 0.100	0.41	0.41	0.41
	9 x 0.067	0.40	0.40	0.40
2	*1 x 0.600*	0.50	0.50	0.50
	1 x 0.300	0.25	0.24	0.24
	2 x 0.300	0.47	0.46	0.46
	4 x 0.300	0.89	0.88	0.89
	8 x 0.300	1.69	1.69	1.71
3	*1 x 0.600*	0.50	0.50	0.51
	0.600 + 0.200 + 0.067	0.68	0.68	0.70
	0.067 + 0.200 + 0.600	0.70	0.69	0.71

ergy delivered by the pendulum device, independent of storage period (Table 2).

Impacting the same site of the tuber with 0.6 J divided over an increasing number of doses (Experiment 1) decreased the percentage of absorbed energy (Table 2). The percentage of absorbed energy decreased slightly with the number of 0.3 J impacts (Experiment 2). The percentage of energy absorbed was not affected by either a decreasing or an increasing order of magnitude of impact energies (Experiment 3). In all experiments the absorbed energy after impact was not affected by the storage period.

Experiment 1

The interaction terms impact energy x potassium level and impact energy x storage period had a significant effect on the volume of discoloured tissue. Splitting of the impact energy into 9 doses reduced the volume of discoloured tissue by 64% on average (Table 3). Damage (volume of discoloured tissue) by impact decreased during storage. Splitting of impact energy was most effective in reducing damage in tubers that were stored for 7 months. Although K1 tubers were more damaged than the K2 tubers, the

Table 3. Volume of discoloured tissue (n = 45) after 4 impact energy (E_{imp} in J) treatments (Experiment 1) in tubers from plants grown at 2 potassium levels (K1, K2) averaged over 3 storage periods (upper part of the table) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over 2 potassium levels (lower part of the table).

Treatment	Volume of discoloured tissue (mm^3)			
	E_{imp} (J)			
	1 x 0.600	3 x 0.200	6 x 0.100	9 x 0.067
K1	1020 ^{bC}	707 ^{bB}	359 ^{aA}	366 ^{bA}
K2	638 ^{aC}	554 ^{aC}	332 ^{aB}	239 ^{aA}
3M	1102 ^{nO}	900 ^{nN}	488 ^{nM}	451 ^{oM}
5M	732 ^{mO}	523 ^{mNO}	393 ^{mMN}	331 ^{nM}
7M	652 ^{mN}	468 ^{mN}	154 ^{mM}	125 ^{mM}

Values within columns followed by the same lower case letter do not differ significantly at the 5% level. Values within rows followed by the same upper case letter(s) do not differ significantly at the 5% level.

Table 4. Depth of discoloured tissue (n = 45) after 4 impact energy (E_{imp} in J) treatments (Experiment 1) in tubers from plants grown at 2 potassium levels (K1, K2) and stored for 3, 5 or 7 months (3, 5, 7M).

Treatment		Depth of discoloured tissue (mm)			
		E_{imp} (J)			
		1 x 0.600	3 x 0.200	6 x 0.100	9 x 0.067
K1	3M	9.1 ^{a}	9.0 ^{ab}	7.1 ^{def}	6.2 ^{fgh}
	5M	7.8 ^{de}	6.5 ^{ef}	5.9 ^{jkl}	5.9 ^{lm}
	7M	7.9 ^{fg}	6.5 ^{fgh}	4.4 ^{klm}	4.1 ^{mn}
K2	3M	8.8 ^{bc}	7.6 ^{cd}	6.3 ^{ghi}	6.3 ^{ijk}
	5M	5.3 ^{fgh}	5.9 ^{ghij}	5.2 ^{mn}	4.2 ^{no}
	7M	5.8 ^{hij}	6.5 ^{ijkl}	4.0 ^{op}	3.4 ^{p}

Values followed by the same letter(s) do not differ significantly at the 5% level.

relative effect of splitting impact energy was the same in both types of tubers.

The interaction term impact energy x potassium level x storage period had a significant effect on the depth of discoloured tissue. The depth of tissue discolouration was less affected (33% reduction on average, Table 4) by splitting impact energy into 9 doses than the volume of discoloured tissue (64%). The second and sixth value of the second column (both 6.5) indicate a significant difference due to the fact that the presented numbers are experimental means instead of predicted values which were used for the statistical analysis. The same phenomenon was observed in Experiment 2 (Table 7). See also statistical analysis in Materials and methods.

Experiment 2

The interaction terms impact energy x storage period and storage period x potassium level had a significant effect on the volume of discoloured tissue. The volume of dis-

Table 5. Volume of discoloured tissue (n = 45) after 5 impact energy (E_{imp} in J) treatments (Experiment 2) in tubers stored for 3, 5 or 7 months (3, 5, 7M) averaged over 2 potassium levels.

Treatment	Volume of discoloured tissue (mm^3)				
	E_{imp} (J) *1 x 0.600*	1 x 0.300	2 x 0.300	4 x 0.300	8 x 0.300
3M	1002 ^{cC}	363 ^{aA}	769 ^{bB}	1071 ^{bC}	1554 ^{bD}
5M	764 ^{bB}	405 ^{aA}	769 ^{bB}	1165 ^{bC}	1432 ^{bC}
7M	409 ^{aA}	265 ^{aA}	335 ^{aA}	587 ^{aB}	741 ^{aB}

Values within columns followed by the same lower case letter do not differ significantly at the 5% level. Values within rows followed by the same upper case letter do not differ significantly at the 5% level.

Table 6. Volume of discoloured tissue (n = 45) in tubers from plants grown at 2 potassium levels (K1, K2) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over 5 impact energy treatments (Experiment 2).

Treatment	Volume of discoloured tissue (mm^3)		
	3M	5M	7M
K1	1206 ^{bC}	1000 ^{bB}	542 ^{aA}
K2	697 ^{aB}	815 ^{aC}	392 ^{aA}

Values within columns followed by the same lower case letter do not differ significantly at the 5% level. Values within rows followed by the same upper case letter do not differ significantly at the 5% level.

coloured tissue increased with the number of 0.3 J impacts (Table 5). The effect varied quantitatively between the various storage periods, but in all cases more impacts caused more damage. Eight times 0.3 J yielded a 3 to 4 times higher volume of discoloured tissue than 0.3 J in one dose. Whether a further increase of the number of impacts would result in increased damage is not clear. As observed before (Table 3) comparable impacts resulted in a lower volume of discoloured tissue in material stored for 7 months, as compared to 3 months (Table 5). K1 tubers were more dam-

Table 7. Depth of discoloured tissue (n = 45) after 4 impact energy (E_{imp} in J) treatments (Experiment 2) in tubers from plants grown at 2 potassium levels (K1, K2) and stored for 3, 5 or 7 months (3, 5, 7M).

Treatment		Depth of discoloured tissue (mm)				
		E_{imp} (J) *1 x 0.600*	1 x 0.300	2 x 0.300	4 x 0.300	8 x 0.300
K1	3M	9.3 ^{c}	6.5 ^{fgh}	8.8 ^{c}	9.4 ^{b}	10.8 ^{a}
	5M	7.1 ^{c}	6.1 ^{gh}	7.8 ^{c}	9.0 ^{b}	9.9 ^{a}
	7M	6.5 ^{efg}	5.0 ^{ij}	6.1 ^{efg}	7.2 ^{cd}	8.9 ^{b}
K2	3M	6.7 ^{de}	3.5 ^{ij}	6.6 ^{de}	7.8 ^{c}	9.3 ^{b}
	5M	7.1 ^{ef}	5.8 ^{ij}	7.2 ^{ef}	8.2 ^{c}	8.8 ^{b}
	7M	5.5 ^{hi}	6.0 ^{k}	5.6 ^{hi}	6.5 ^{efg}	8.0 ^{c}

Values followed by the same letter(s) do not differ significantly at the 5% level.

aged than K2 tubers (Table 6).

The interaction term impact energy x potassium level x storage period had a significant effect on the depth of discoloured tissue. The depth of discoloured tissue was less when the dose was reduced from 0.6 to 0.3 J, but increased proportionally with the number of 0.3 J impacts (Table 7). The same tendency was found for the parameter volume of discoloured tissue (Table 5).

Experiment 3

The interaction terms impact energy x potassium level and storage period x potassium level had a significant effect on the volume of discoloured tissue. A decreasing and an increasing order of impact energy caused the same volume of discoloured tissue (Table 8). As observed before (Experiment 1 and 2) K1 tubers were more dam-

Table 8. Volume of discoloured tissue (n = 45) after 3 impact (E_{imp} in J) treatments (Experiment 3) in tubers from plants grown at 2 potassium levels (K1, K2) averaged over a 3, 5 or 7 months storage period.

Treatment	Volume of discoloured tissue (mm^3)		
	E_{imp} (J)		
	1 x 0.600	0.600 + 0.200 + 0.067	0.067 + 0.200 + 0.600
K1	1038 ^{bB}	909 ^{bA}	926 ^{bA}
K2	546 ^{aA}	661 ^{aB}	666 ^{aB}

Values within columns followed by the same lower case letter do not differ significantly at the 5% level.
Values within rows followed by the same upper case letter do not differ significantly at the 5% level.

Table 9. Volume of discoloured tissue (n = 45) in tubers from plants grown at 2 potassium levels (K1, K2) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over 3 impact treatments (Experiment 3).

Treatment	Volume of discoloured tissue (mm^3)		
	3M	5M	7M
K1	924 ^{bB}	1096 ^{bB}	853 ^{bA}
K2	777 ^{aB}	752 ^{aB}	346 ^{aA}

Values within columns followed by the same lower case letter do not differ significantly at the 5% level.
Values within rows followed by the same upper case letter do not differ significantly at the 5% level.

Table 10. Depth of discoloured tissue (n = 45) in tubers from plants grown at 2 potassium levels (K1, K2) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over 3 impact treatments (Experiment 3).

Treatment	Depth of discoloured tissue (mm)		
	3M	5M	7M
K1	8.7 ^{a}	8.6 ^{b}	8.1 ^{c}
K2	8.2 ^{c}	7.5 ^{c}	5.5 ^{d}

Values followed by the same letter do not differ significantly at the 5% level.

aged than K2 tubers (Tables 8 and 9).

The interaction term storage period x potassium level had a significant effect on the depth of discoloured tissue (Table 10). The depth of tissue discolouration was not affected by the sequence of magnitude of the impact series (data not shown) and decreased with the potassium level and the storage period.

Discussion

Experimental conditions

Pendulum device. The pendulum device proved to be an adequate tool to exactly control and measure the delivery and absorbance of energy, and to study the effects of (repetitive) impacts on subcutaneous tissue discolouration. Over the chosen energy range clear effects of energy and number of impacts on the depth and volume of tissue discolouration, as a measure of subcutaneous damage, were observed. The volume and depth of discoloured tissue ranged from 0 (controls without impacts) to 6.8 cm , and from 0 to 1.7 cm, respectively. In contrast to other reports on pendulum experiments external damage was observed in none of the tubers tested. It is not known what the effect would have been in case of a non-spherical impact body.

Storage, potassium level and susceptibility. In all experiments the damage by impact decreased during storage. The susceptibility to tissue discolouration, measured prior to the impact experiments after the tubers were kept 3 days at 15 °C, increased up to 5 months of storage but fell after 7 months (Table 1). The decrease after 7 months may be due to the sprouting that occurred at that moment. Prior to the impact experiments the tubers were transferred to 10 °C (at 93% RH) for *ca* 1 week. Sprouting progressed in the order 3–7 months. However, the tubers remained firm probably due to the high RH. Maintenance of firmness is also suggested by the data on energy absorption during impact (Table 2). A decrease in volume and depth of discoloured tissue through impacts after 5 and 7 months storage could be accounted for by a decreasing dry matter content due to sprouting in the week before impact (data not shown). Although a study of the effect of storage was not the purpose of our work, our results are contradictory to the often reported explanation that tuber firmness decreases upon storage due to moisture loss and consequently the susceptibility to tissue discolouration increases (Ophuis *et al.*, 1958; Hughes, 1980). Kunkel & Gardner (1959) reported that sprouted tubers were less prone to tissue discolouration. Their data refer to flaccid tubers. Furthermore the storage conditions (no sprout inhibitors, 93% RH, 4.5 °C, individual storage) in our experiments were different from storage conditions reported elsewhere. In general K1 tubers were more damaged than K2 tubers. The former had a higher DM content (Table 1) and DM content is positively related to susceptibility to tissue discolouration (Burton, 1969; Hughes, 1974, 1980, see also Table 1). Van Es (1975) reported a negative relation between tuber potassium content and blackspot susceptibility. Potassium has an effect on the elasticity of the cell walls, on the size of the starch granules, on the specific gravity of the tuber

and on the turgor pressure potential. Hughes *et al.* (1975) found that the volume of discoloured tissue was inversely related to the dose of K fertilizer.

Impact dose-effect relationship

Dose split. Splitting 0.6 J over 9 impacts yielded an average reduction of the depth of tissue damage of 33% (Table 4) and an average reduction of the volume of discoloured tissue of 64% (Table 3), relative to one impact of 0.6 J. The larger effect on volume (tridimensional) than on depth (unidimensional) suggests that the absorption and transfer of impact energy is not unidirectional. This finding is corroborated by the observation that the cross section of discoloured tissue has an ellipsoidal shape. Nerinckx & Verschoore (pers. comm.) found a larger reduction (92%) in the volume of tissue discolouration when 0.9 J was divided over 3 impacts with a pendulum device to which a non-spherical impact body (diameter 45 mm) was mounted. Their experiments were done at 7 °C with heel end halves of cv. Bintje. The difference in volume and depth of discoloured tissue between the impact treatments 6 × 0.1 and 9 × 0.067 J was minimal. The difference in absorbed energy after these two impact treatments was also negligible (Table 2). It is not known whether the splitting of impact energy over more than 9 impacts would result in the same, more or less tissue discolouration. Parke (1963) found the amount of energy absorbed by potato tubers after one impact to be positively related to the volume of discoloured tissue.

Repetitive impacts. The volume and depth of discoloured tissue increased with the number of 0.3 J impacts (Experiment 2, Tables 5 and 7). It is not clear whether a further increase of the number of impacts, especially after a storage period of 3 months, would result in an increased amount of discoloured tissue. Nerinckx & Verschoore (pers. comm.) similarly found an increase of the volume of discoloured tissue with the number of 0.9 J impacts.

Sequential impacts. A sequence of impacts of unequal energy either in a decreasing or an increasing order did not affect the degree of tissue discolouration (Experiment 3, Tables 8 and 9). Nerinckx & Verschoore (pers. comm.) found that the volume of discoloured tissue was doubled after a sequence with impacts in a decreasing order (1.08, 0.54 and 0.36 J), relative to an increasing order.

In our experiments no impact doses were used that cause external damage. In other reports on the dose-effect relationship the resulting damage is usually a mixture of external damage and subcutaneous tissue discolouration.

Practical implications

In our experiments on the effect of impact energy on tissue discolouration the chosen conditions differed from those in commercial potato lines. Tubers were stored individually on soft ventilating pads at 4.5 °C, and no other source of tissue discolouration than the experimental impacts existed. In practice storage in bulk, a higher temperature and the application of sprout inhibitors are common. Furthermore, the ab-

sence of mechanical damage, resulting in zero tissue discolouration, seldomly occurs in practice. These differences in tuber treatment may affect the dose-effect relationship, but are difficult to circumvent when defined and standardized conditions are to be used in an experimental framework. The time between consecutive experimental impacts was *ca* 10 s. In practice this interval may vary from less than 1 second to various months. Recuperation of the tissue may depend on impact interval. Also each tuber piece was impacted at one well-defined site, while in practice impact sites are many and occur all over the surface of the tuber (Molema *et al.*, 1995). The assessment of discolouration, although different from the practical appreciation of this phenomenon, was precise and detailed. Nevertheless the assay of tissue discolouration remains in part subjective. Image processing or a non-destructive method could significantly improve the results, experimentally as well as practically. A major part of the variation in tissue discolouration (volume and depth) is probably caused by the variation in dry matter content that occurs between tubers from the same stem of the potato plant (Veerman *et al.*, 1996).

Although data from the experiments presented here may be confounded with the specific choice of experimental conditions, there appears to be no alternative to obtain equally detailed information about the impact dose-effect relationship: a number of low energetic impacts is clearly harmful; a number of small impacts is less harmful than one bigger impact; discolouration increases with the number of impacts. Future potato handling lines may take these findings into account, by lowering the number and energy of impacts.

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List of abbreviations

DM = dry matter, d = day, FW = fresh weight, RH = relative humidity, s.d. = standard deviation of the mean.