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Effect of impact body shape on subcutaneous tissue discolouration in potato tubers

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Abstract

In the modern potato industry the economies of scale demand that all production and handling processes must be highly mechanized. Mechanization is usually associated with increased damage. The shape of impacting surfaces is an important factor that affects damage in potatoes.

We investigated the relation between the radius of curvature of the impact body at a given level of energy and the resulting volume and depth of discoloured tissue as measure of damage. Tubers were impacted at a desired rate and by a desired impact body shape with a computer-controlled pendulum. The tubers were from plants grown at two different levels of potassium fertilizer (i.e. susceptibilities to tissue discolouration) and stored for 3, 5 or 7 months.

A spherical impact body doubled the volume and depth of discoloured tissue, relative to a non-spherical impact body. The differences in volume and depth of discoloured tissue after impact with spherical impact bodies (radii of curvature 30 or 15 mm) was minimal. Reducing the impact energy from 0.600 to 0.067 J yielded an average reduction of the volume of discoloured tissue of *ca* 95% and an average reduction of the depth of discoloured tissue of *ca* 80%.

Future potato handling lines may take these findings into account, by lowering the use of spherical impact bodies and the level of impact energy.

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

Introduction

The economies of scale in the modern potato industry demand that all the production and handling processes must be highly mechanized. Mechanization, however, is usually associated with increased damage. From the field to the shop, table potatoes are exposed to many impacts (mechanical forces). Goldsmith (1960) defined impact as 'a collision between bodies where the resulting forces are exerted and removed in a very short period of time and initiate stress waves which travel away from the region of contact'.

Potato tuber damage has been categorized into external and internal damage. An important type of damage caused by impact 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). In general the phenomenon comprises damage to plant tissue by external forces causing a change in texture and/or alteration of colour, flavour and texture (Mohsenin, 1986). This phenomenon occurs in every step of harvesting and handling operations (Nelson & Mohsenin, 1968).

Impact is caused by drops and changes in speed and direction of tubers and by tuber to tuber contacts. In the average handling chain in the Netherlands a single potato is impacted 340 times (Molema & Bouman, 1996). The effect of repetitive impacts on subcutaneous tissue discolouration was described by Molema *et al.* (1997). Splitting of the impact energy (0.6 J) over various doses considerably reduced the volume and depth of discoloured tissue. The volume and depth of discoloured tissue increased with the number of 0.3 J impacts. A decreasing and an increasing order of magnitude of impact energy caused the same level of tissue discolouration.

Impacts can be caused by impact bodies of different shape. For instance the potato harvester is equipped with sieving webs containing rod bars (small radius of curvature (r.o.c.)), while tubers can also be impacted by the steel plate wall of bunkers (r.o.c.∞). Also, the r.o.c. of tubers varies considerably. Mathew & Hyde (1992) found that the shape of the impacting surface is an important factor that affects bruising in potatoes.

The relations between the r.o.c. of the impact body at a given level of energy and the resulting volume and depth of discoloured tissue are not known and were therefore investigated using a pendulum (Grant & Hughes, 1985; Molema *et al.*, 1997; Noble, 1985; Skrobacki *et al.*, 1989).

This work addresses two questions:

- What is the effect of the radius of curvature of the impact body on the volume and depth of discoloured tissue at a given level of impact energy?
- Is there interaction between impact energy level and impact body shape in relation to the volume and depth of discoloured tissue?

Materials and methods

Growing and storage of the tubers

The potato tubers (*Solanum tuberosum* L., cv. Bintje, grade 50–60 mm) were produced, harvested and stored as described by Molema *et al.* (1997). The grade 50–60 mm was selected by means of templates. To induce differences in susceptibility to tissue discolouration the plants were given a low (K_L) or a high (K_H) level of potassium fertilizer. The tubers were harvested manually and stored individually on soft ventilating pads to minimize mechanical damage.

Three, five or seven months after harvest the potatoes were removed from the cold store for pendulum experiments.

The pendulum

A computer-controlled pendulum (Molema *et al.*, 1997) was used (Figure 1) to impact tubers at a desired energy level. The impact energy is determined by the initial angle (α) of the pendulum, the weight of the pendulum arm and of the impact body, the shape of the pendulum arm and of 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 experiment a non-spherical (r.o.c. = ∞, encoded B∞) and two spherical impact bodies (r.o.c. 30 (B30) and 15 mm (B15)) were used. The impact body diameter was 30 mm.

Preparation of the tubers

Potatoes were cut longitudinally into pieces with a maximum thickness of 30 ± 1 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

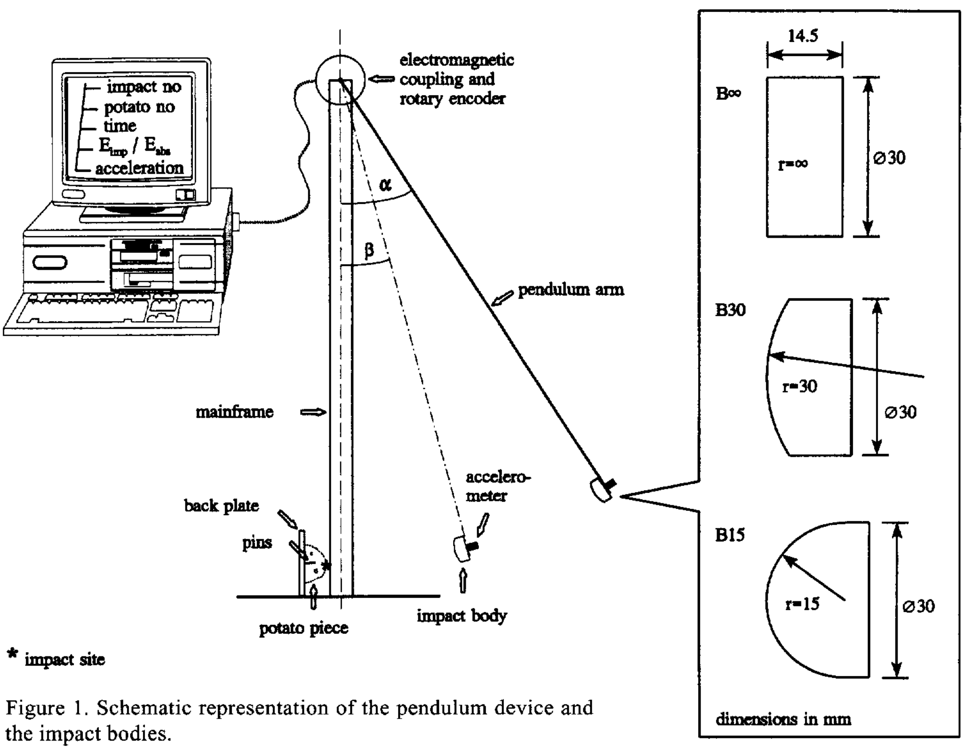

Figure 1. Schematic representation of the pendulum device and the impact bodies.

1 mm). Finney (1963) found no difference in the effect of impacts between whole and halved tubers. 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 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). The impact site was marked and its radius of curvature was measured lengthwise and broadwise as reported by Molema *et al.* (1997).

Experiment

An impact energy of 0.6 J, which frequently occurs in practice (Molema *et al.*, 1995, 1997), was taken as a standard. This energy level did not cause external damage. Parke (1963) reported that a minimum energy level of 0.136 J was required to produce internally-bruised tissue.

Per treatment (combination of impact type, potassium level and storage duration) 45 tubers were impacted. The experiment was done at 10°C and the tubers were transferred to 10°C and 93% RH *ca* 2 weeks prior to the impact experiment. After impact the tuber pieces were stored at 20°C for 4 days according to the protocol described by Molema *et al.* (1995). The experiment comprised nine treatments.

Treatment 1–3: impact energy of 0.6 J, impact body shape with r.o.c. = ∞, 30 and 15 mm, respectively.
Treatment 4–5: impact energy of 0.2 J, impact body shape with r.o.c. = ∞, 30 and 15 mm, respectively.
Treatment 6–9: impact energy of 0.067 J, impact body shape with r.o.c. = ∞, 30 and 15 mm, respectively.

All doses were given as one impact.

Four days after the impacts the volume and depth of the discoloured tissue were determined. The experiment was done with tubers stored for 3, 5 or 7 months (referred to as 3M, 5M and 7M, respectively) and grown at 2 potassium levels (K_L and K_H).

Impact characteristics

Impact characteristics (acceleration *vs* duration) were recorded of the nine treatments of K_H tubers after 5 months storage.

Assays

The dry matter content (calculated from under-water weight as reported by Rastovski *et al.*, 1987) and the susceptibility to tissue discolouration, at harvest and at the start of the experiment, were determined 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 as described by Molema *et al.* (1997).

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

Statistical analysis

The way the data of volume and depth of discoloured tissue were statistically analysed is described in detail by Molema *et al.* (1997).

Volume of discoloured tissue

The tubers were categorized into ordered classes according to their volume of discoloured tissue. For the analysis the following threshold model was used:

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

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 effects belonging to the design matrix *X*; *u* is the vector with random effects and *Z* the design matrix belonging to *u* as explained by Molema *et al.* (1997).

The data were analysed with the procedure CLASS (Keen, 1994) belonging to the statistical package Genstat (Payne *et al.*, 1993).

Depth of discoloured tissue

The model used for the depth of discoloured tissue was:

$$\log(y) = Xb$$

in which *y* is the depth of discoloured tissue. These depth data were analysed with the statistical package Genstat (Payne *et al.*, 1993).

In the tables the means of experimental data are presented, while the statistical analyses refers to values predicted by the described models.

Results

General observations

At the onset of the experiments the tubers were free of tissue discolouration. The absolute dry matter content of K_L tubers was *ca* 2% higher than that of K_H 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).

Table 1. Dry matter content and susceptibility to discolouration (Molema *et al.*, 1995) in tubers grown at a low and high potassium level (K_L, K_H) and stored for 0, 3, 5 or 7 months (0, 3, 5, 7M).

Storage duration	Dry matter content (%)		Susceptibility to discolouration (index)	
	K_L	K_H	K_L	K_H
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

The average fresh weight (127 ± 29 g) and dimensions (length 83 ± 10 mm, width 55 ± 4 mm) of the tubers and r.o.c. at the impact site (r.o.c. 55 ± 18 mm lengthwise and 19 ± 3 mm broadwise) were neither affected by storage duration, nor by the potassium treatment during tuber production (data not shown). The potato pieces had an average weight of 68 ± 12 g (FW), a length of 82 ± 10 mm, a width (perpendicular to the maximum width of the whole tuber) of 45 ± 4 mm and the impact site 30 ± 1 mm from the backplate of the pendulum device. Over all treatments, the tubers absorbed 75 to 85% of the energy delivered by the pendulum device, independent of storage duration and impact body shape (Table 2). The energy absorbance was positively correlated with the impact energy. Potassium level (K_L/K_H) did not affect the energy absorbance.

In general, the volume and depth of discoloured tissue due to impact treatment increased during storage up to 5 months, but fell after seven months (Tables 3, 4 and 5). K_L tubers were more damaged by impact than K_H tubers (Tables 3, 4, 5 and 6). The radius of curvature at the impact site of the tuber also affected tissue discolouration. The effect of the lengthwise curvature of the tuber on volume and depth of dis-

Table 2. Impact energy (E_{imp}) and absorbed energy (E_{abs}) in tubers of nine treatments averaged over 2 potassium levels (K_L, K_H). The impact energy treatments were carried out with three impact body shapes (B∞, B30, B15). All energies in J. Tubers were stored for 3, 5 or 7 months (3, 5, 7M). (standard deviation).

Treatment		E_{abs}(J)		
E_{imp}(J)	Impact body	3M	5M	7M
0.600 (0.001)	B∞	0.501 (0.007)	0.498 (0.007)	0.508 (0.008)
0.600 (0.001)	B30	0.502 (0.006)	0.498 (0.005)	0.509 (0.004)
0.600 (0.001)	B15	0.503 (0.005)	0.500 (0.004)	0.510 (0.005)
0.200 (0.001)	B∞	0.160 (0.004)	0.156 (0.003)	0.159 (0.003)
0.200 (0.001)	B30	0.161 (0.003)	0.157 (0.002)	0.159 (0.002)
0.200 (0.001)	B15	0.161 (0.003)	0.158 (0.002)	0.160 (0.002)
0.067 (0.001)	B∞	0.053 (0.003)	0.050 (0.001)	0.050 (0.001)
0.067 (0.001)	B30	0.052 (0.002)	0.050 (0.002)	0.050 (0.001)
0.067 (0.000)	B15	0.052 (0.002)	0.050 (0.001)	0.051 (0.001)

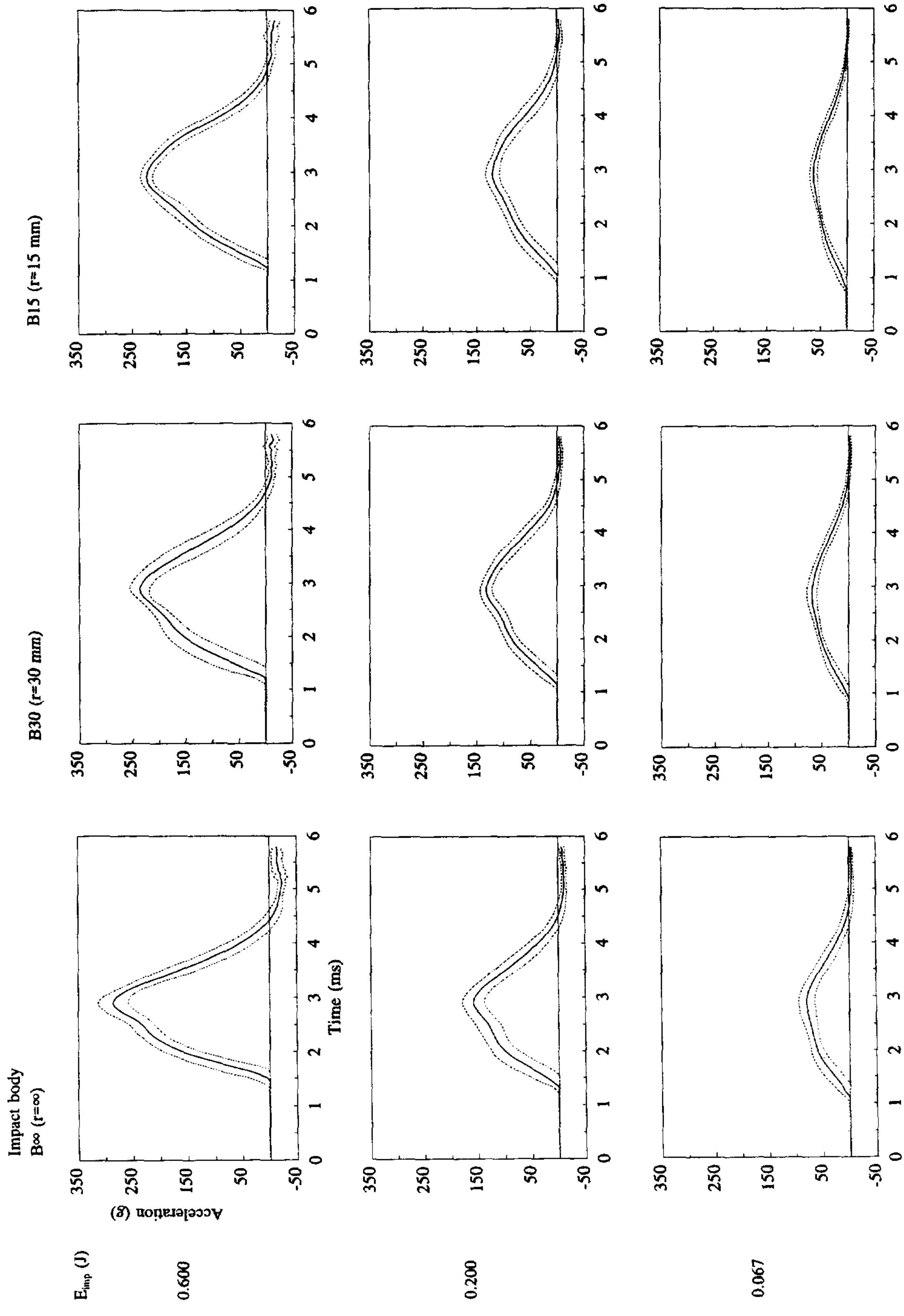

Figure 2. Impact characteristics of K_H tubers after 5 months storage given for nine impact treatments. Acceleration (*g*) versus time (*ms*). Bold lines represent mean values (n = 20); dotted lines define $\bar{x} \pm 1.96$ S confidence interval.

coloured tissue was significant (data not shown). Tissue discolouration decreased with the lengthwise radius of curvature. There was no significant effect of the broadwise curvature of the tuber.

Impact characteristics

Impact characteristics of K_H tubers after 5 months storage showed that the spherical impact bodies gave a lower peak acceleration and a longer impact duration, relative to the flat impact body (Figure 2). Variation between impact curves of identical treatments was minimal. Lower impact energies gave lower peak accelerations. Impact duration was hardly affected by impact energy. The difference between the impact characteristics of the two spherical impact bodies (B30 and B15) was minimal.

Subcutaneous tissue discolouration

The numbers presented in the tables 3 to 6 are experimental means instead of predicted values which were used for the statistical analysis.

Volume of discoloured tissue. The interaction terms impact energy × potassium level and impact energy × storage duration had a significant effect on the volume of discoloured tissue. Decreasing the impact energy from 0.600 to 0.200 or 0.067 J reduced the volume of discoloured tissue by *ca* 75 and 95% on average, respectively. Although in K_H tubers, damage was on average *ca* 30% less than in K_L tubers, the relative effect of lowering the impact energy was the same in both types of tubers (Table 3).

The interaction terms impact body shape × potassium level and impact body shape

Table 3. Volume of discoloured tissue (n = 45) after 3 impact energy treatments (E_{imp} in J) in tubers from plants grown at a low and high potassium level (K_L, K_H) averaged over 3 storage durations and 3 impact body shapes (upper part of the table) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over 2 potassium levels and 3 impact body shapes (lower part).

Treatment	Volume of discoloured tissue (mm³)		
	E_{imp} (J)		
	0.600	0.200	0.067
K_L	681 ^{aA}	167 ^{aB}	28 ^{aC}
K_H	499 ^{bA}	119 ^{bB}	19 ^{bC}
3M	622 ^{nM}	102 ^{oN}	5 ^{nO}
5M	697 ^{mM}	196 ^{mN}	37 ^{mO}
7M	452 ^{oM}	131 ^{nN}	27 ^{mO}

Values within columns followed by the same lower case letter and values within rows followed by the same capital letter do not differ significantly at the 5% level. Results of the treatments 'potassium' and 'duration' are not to be compared.

× storage duration also had a significant effect on the volume of discoloured tissue. The spherical impact bodies (B30 and B15) doubled to tripled the volume of discoloured tissue relative to the non-spherical impact body. The difference in radii of curvature of the two spherical impact bodies had a little or no effect on the volume of discoloured tissue (Table 4).

In K_H tubers the volume of discoloured tissue was *ca* 17 to 46% less, compared to K_L tubers. The reduction increased with the radius of curvature. The largest relative differences between tissue damage after storage were caused by the flat impact body. There was no significant interaction between impact energy and impact body shape in relation to the volume of discoloured tissue.

Depth of discoloured tissue. The interaction terms impact energy × potassium level, impact energy × storage duration, impact energy × impact body shape and impact body shape × potassium level had a significant effect on the depth of discoloured tissue.

Lowering the impact energy from 0.600 to 0.200 or 0.067 J had less effect on the depth of discoloured tissue (*ca* 50 and 80% reduction on average, respectively, Table 5) than on the volume of discoloured tissue (*ca* 75 and 95% reduction on average, respectively, Table 3). In K_H tubers the damage (depth of discoloured tissue) was *ca* 15% less at 0.600 J and 50% less at 0.067 J, compared to K_L tubers.

A non-spherical impact body (B∞) halved the depth of discoloured tissue on average as compared to the spherical impact bodies (B30 and B15). Relatively the difference between the effect of the two types of impact bodies (non-spherical and spherical) on the depth of discoloured tissue was the smallest at the highest impact energy. A reduction of the impact energy from 0.600 to 0.067 J was most effective with B∞ (*ca* 90% reduction). There was a small difference in depth of discoloured tissue after treatment with B30 or B15.

Table 4. Volume of discoloured tissue (n = 45) after 3 impact body treatments (B∞, B30, B15) in tubers from plants grown at a low and high potassium level (K_L, K_H) averaged over 3 storage durations and 3 impact energy treatments (upper part of the table) and stored for 3, 5 or 7 months (3, 5, 7M) averaged over 3 impact energy treatments and 2 potassium levels (lower part of the table).

Treatment	Volume of discoloured tissue (mm^3)		
	Impact body		
	B∞	B30	B15
K_L	183 ^{aC}	348 ^{aA}	346 ^{aB}
K_H	98 ^{bB}	253 ^{aA}	286 ^{bA}
3M	97 ^{oO}	304 ^{nN}	328 ^{mnM}
5M	212 ^{mN}	365 ^{mM}	353 ^{mM}
7M	111 ^{nO}	232 ^{nN}	267 ^{nM}

Values within columns followed by the same lower case letter and values within rows followed by the same capital letter do not differ significantly at the 5% level. Results of the treatments 'potassium' and 'duration' are not to be compared.

Table 5. Depth of discoloured tissue (n = 45) after 3 impact energy treatments (E_{imp} in J) in tubers from plants grown at a low and high potassium level (K_L, K_H) averaged over 3 storage durations and 3 impact body shapes (upper part of the table), stored for 3, 5 or 7 months (3, 5, 7M) averaged over 2 potassium levels and 3 impact body shapes (middle part) and with 3 impact body shapes (B∞, B30, B15) averaged over 2 potassium levels and 3 storage durations (lower part).

Treatment	Depth of discoloured tissue (mm)		
	E_{imp} (J)		
	0.600	0.200	0.067
K_L	7.4 ^{a}	3.8 ^{c}	2.0 ^{e}
K_H	6.3 ^{b}	3.2 ^{d}	1.0 ^{f}
3M	7.0 ^{k}	2.8 ^{o}	1.5 ^{p}
5M	7.3 ^{j}	4.2 ^{m}	1.6 ^{q}
7M	6.2 ^{l}	3.4 ^{n}	1.4 ^{r}
B∞	5.1 ^{v}	1.5 ^{x}	0.4 ^{z}
B30	7.6 ^{u}	3.8 ^{w}	2.3 ^{x}
B15	7.8 ^{u}	5.0 ^{v}	1.7 ^{y}

Values followed by the same letter do not differ significantly at the 5% level. Results of the treatments 'potassium', 'duration' and 'shape' are not to be compared.

As observed before (Table 5) the depth of discoloured tissue doubled when tubers were impacted with the spherical impact bodies, relative to the non-spherical impact body (Table 6). There was no significant difference in the effect on the depth of discoloured tissue between the two spherical impact bodies. As observed before (Table 4) K_L tubers were more damaged than K_H tubers. The damage reduction in K_H tubers, relative to K_L tubers, increased more with the r.o.c. of the impact body.

The lengthwise radius of curvature of the tubers had a significant effect on depth and volume of discoloured tissue. A larger radius of curvature lengthwise was correlated with a smaller volume and depth of discoloured tissue (data not shown).

Table 6. Depth of discoloured tissue (n = 45) after 3 impact body treatments (B∞, B30, B15) in tubers from plants grown at a low and high potassium level (K_L, K_H) averaged over 3 storage durations and 3 impact energy treatments.

Treatment	Depth of discoloured tissue (mm)		
	Impact body		
	B∞	B30	B15
K_L	2.7 ^{c}	5.1 ^{a}	5.4 ^{a}
K_H	2.0 ^{d}	4.0 ^{b}	4.4 ^{b}

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

Discussion

Experimental conditions

Pendulum device. The pendulum device proved to be an adequate tool to study the effect of impact body shape and impact energy on subcutaneous tissue discolouration. The deliverance and absorption of energy proved to be highly reproducible. Over the chosen energy range and radii of curvature clear effects of impact energy and impact body shape 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 2363 mm^3, and from 0 to 13 mm, respectively. Variation in tissue discolouration within treatments was considerable. No minimum threshold energy level has been reported that will surely cause tissue damage in potatoes. Parke (1963) reported that potato structure plays an important role in the incidence of damage; e.g. one sample was damaged at 0.09 J while another absorbed 0.6 J and exhibited no damage. Also Ghadge (1988) reported that variation in tissue discolouration was high; some tubers were damaged at an energy level of 0.4 J and some required at least 0.7 J to be damaged. In contrast to other reports on pendulum experiments external damage was observed in none of the tubers tested in our experiment.

Independent of the impact body shape the tubers absorbed 75 to 85% of the energy delivered by the pendulum device. Parke (1963) also reported that the effect of bar diameter upon energy absorption was extremely small.

Storage, potassium level and susceptibility. As observed before (Molema *et al.*, 1997) 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 same tendency was found for tissue discolouration after the impact treatments. The decrease after 7 months is ascribed to the sprouting that had started at that moment (Molema *et al.*, 1997). In general K_L tubers were more damaged by impact than K_H tubers. The former had a higher dry matter content (Table 1) and dry matter content is positively related to susceptibility to tissue discolouration (Burton, 1969; Hughes, 1974, 1980a, see also Table 1). Van Es (1975) reported a negative relation between tuber potassium content and blackspot susceptibility.

Impact characteristics

The impact characteristics (Figure 2) illustrate the effect of impact energy and impact body shape on the duration and magnitude of impact stress. The pattern of acceleration after impact was only recorded for K_H tubers, stored for 5 months. Differences in the characteristics of the two spherical impact bodies were negligible. Similarly, the depth and volume of discoloured tissue were not differentially affected by B30 and B15.

The non-spherical impact body gave higher peak accelerations, relative to the spherical ones. This phenomenon is caused by the larger contact area during impact. The inprint of the flat impact body was less than that of the spherical ones. The quick deceleration of the flat impact body results in a high peak acceleration and a short impact duration.

Variation in impact characteristics within treatments was small and is probably caused by tuber firmness and radius of curvature of the impact site of the tuber (Noble, 1985). Noble also reported that impact duration has a critical effect on the type and extent of resultant tissue damage. For the same amount of absorbed energy, impacts of relatively long duration resulted in more blackspot and internal crushing whereas impacts of relatively short duration resulted in more internal shattering. In our experiment internal shattering was not observed.

Impact body shape

The volume and depth of discoloured tissue (Tables 4, 5 and 6) was doubled by the spherical impact bodies, relative to the non-spherical impact body. On average damage reduction (volume and depth) increased with the r.o.c. of the impact body. The same tendency was found for the lengthwise radius of curvature of the tuber. The differences in volume and depth of discoloured tissue after impacts with the spherical impact bodies B30 and B15 were small.

Thornton *et al.* (1974) and Hughes (1980b) reported that tubers with small radii of curvature (e.g. with oblong tubers) are particularly prone to damage. Hesen & Kroesbergen (1960) reported a negligible difference in percentage of damaged tubers when impacted by rods with a diameter of 4 and 7 mm respectively (77 *vs* 74%). Volbracht & Kuhnke (1956), using a drop test, reported that tuber damage was reduced by the use of bars with a larger diameter. Parke (1963) reported a general reduction in the volume of damaged tissue by using larger diameter bars. The effect of the bar diameter in his experiments was not large.

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.

Impact energy

Reducing the impact energy from 0.600 to 0.067 J yielded an average reduction of the depth of damaged tissue of *ca* 80% (Table 5) and an average reduction of the volume of discoloured tissue of *ca* 95% (Table 3). In our previous work (Molema *et al.*, 1997) the same phenomenon was found. Parke (1963) also reported a positive correlation between impact energy and volume of discoloured tissue.

Contradictory to the results of Parke (1963) where a minimum energy level of 0.136 J was required to produce tissue damage, we found that 0.067 J already yields tissue discolouration (bruising). In our experiment, however, another cultivar was used and the way of tuber preparation also differed of that of Parke (1963).

Practical implications

The conditions in commercial potato handling lines differ from the conditions chosen in our experiment. Tubers were not stored in bulk, but individually on soft ventilating pads, and at 4.5°C. Moreover, no other source of tissue discolouration than the experimental impacts existed. Also each tuber piece was impacted at one well-defined site. These differences in tuber treatment may modulate the effect of the shape of the impact body and of the energy dose.

By lowering the impact energy the volume of discoloured tissue decreased more than proportionally. The depth of discoloured tissue also decreased but less than volume did. In this relationship the r.o.c. of the impact body was of great importance. A ∞ r.o.c. gave the least tissue discolouration. The rate of curvature of spherical impact bodies, at least between 30 and 15 mm, seems to be less important. Radius of curvature at the impact site of the tuber also affects tissue discolouration. The same tendency observed for impact body curvature was found for the effect of lengthwise tuber curvature on depth and volume of discoloured tissue.

A significant effect of broadwise tuber curvature was not established, probably due to the small range of broadwise radii of curvature (19 ± 3 mm). To obtain a link to practice we measured the minimum and maximum radii of curvature of 150 randomly-selected ungraded potatoes (cv. Bintje) and found that r.o.c. ranged from 13 mm to ∞ (hollow sites were not taken into account). This means that, in practice (ungraded potatoes), the radii of curvature of impacted tuber sites are of great influence on the resulting amount of tissue damage.

It is of great importance to know whether 'round' or more flat 'rectangular' tubers are preferred in relation to the susceptibility to tissue discolouration. This because more flat like tubers have both small as well as large radii of curvature. The total amount of tissue discolouration may be the same as in spherical ones but in the tubers with large flat areas at their sites of high curvature (small r.o.c.) a larger volume and depth of tissue discolouration, and due to this more peel losses, may occur. It is important to gather information about the chance of impacting a defined tuber site (small/large radius of curvature) in a handling chain to get information about the desired tuber shape. The disadvantage of nearly perfectly spherical tubers (a small range in radii of curvature) is the high chance of rolling during handling resulting in more kinetic energy which gives a higher chance on tissue discolouration.

Future potato handling lines may take the findings of this research into account, by lowering the use of spherical impact bodies and the level of impact energy.

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List of abbreviations

DM = dry matter, FW = fresh weight, RH = relative humidity, s.d. = standard deviation, $\bar{x}$ = sample mean, S = square root of the sample variance, vs = versus.

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